Prepared for
George C. Marshall Space Flight Center
Huntsville, Alabama
Contract No. NAS8-21024

FINAL REPORT

DEFINITION OF EXPERIMENT PROGRAM IN SPACE OPERATIONS, TECHNIQUES AND SUBSYSTEMS

Independent Manned Manipulator (IMM),
Task Addendum #1 - Design, Breadboard
and Testing of an Experimental Grappling
Manipulator and Controller
Report No. 00.960
July 1967

Prepared by
Advanced Maneuvering Systems

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FOREWORD

The work presented in this report was performed by the Missiles and Space Division - Texas (MSD-T) of the LTV Aerospace Corporation under NASA Contract NAS8-21024. The contract was initiated as a Task Addendum to Contract NAS8-20316, Independent Manned Manipulator (IMM). The work was accomplished under the direction of the Manufacturing Engineering Laboratory of the George C. Marshall Space Flight Center, Huntsville, Alabama, with Mr. Vaughn H. Yost as Contracting Officer's Representative,

The Program Manager for MSD-T was Mr. J. B. Griffin, Manager of Advanced Maneuvering Systems. Mr. W. C. Boyce was Project Engineer and principal designer. The Technical Project Engineer for Electrical/Electronics was Mr. M. C. Bean. Mr. Boyce was principal author of this report.

Sincere appreciation is expressed for the cooperation of the Technologies Branch of the MSD-T Engineering Department for their in-house support of this contractual effort. Under an Applied Research program, conducted with MSD-T funds, an air-bearing test vehicle for the MSD-T frictionless platform facility was designed and fabricated, six developmental hydrazine reaction control motors were purchased, and a complete hydrazine propulsion system was designed and installed on the test vehicle. This system was supplemented by a Control Electronics Unit and a Gyro Package borrowed from the Astronaut Maneuvering Unit (AMU) Program. Significant capital improvements to the Maneuvering Unit Systems Test Lab (MUSTL) were also required to make the facility safe for manned testing with hydrazine.

Acknowledgement is also given to the Aerospace Division of Walter Kidde & Co., Inc. for their generosity and cooperation in furnishing the Ballscrew used in the tong actuating system.

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LIST OF ABBREVIATIONS

AC	=	alternating current
amp	=	Ampere
AMU	=	Astronaut Maneuvering Unit
cfm	=	cubic feet per minute
CG	=	Center of Gravity
cm	=	centimeter
cps	=	cycles per second
CSM	=	Command Service Module
DC	=	direct current
deg	=	degree
fps	=	feet per second
ft	=	feet
G	=	gravity
Gen	=	generator
Hz	=	Hertz - cycles per second
IMM	=	Independent Manned Manipulator
in	=	inch
lb	=	pound
LEM	=	Lunar Excursion Module
m	=	meter
min	=	minute
mps	=	meters per second

LIST OF ABBREVIATIONS (con't)

MSD-T	=	Missiles and Space Division, Texas, Division to LTV Aerospace Corp.
MUSTL	=	Maneuvering Unit Systems Test Laboratory
mv	=	millivolt
MWP	=	Maneuvering Work Platform
N	=	Newton
N-m	=	Newton - meters
N/m^2	=	Newtons per square meter
oz	=	ounce
Ø	=	Phase
psi	=	pounds per square inch
rpm	=	revolutions per minute
see	=	second
sw	=	switch.
Tach	=	tachometer
v	=	volt

1.0 INTRODUCTION AND SUMMARY

Planning studies for future space exploration activities have shown requirements for small, manned, utility spacecraft capable of a high degree of versatility and maneuverability. These vehicles, designated Independent Manned Manipulator Units (IMM), possess greater functional versatility, longer range and mission duration, increased maneuverability and superior support capability than do conventional back pack maneuvering units or similar individual maneuvering devices. Many of these additional attributes are due to their support load-carrying capability and their ability to maneuver while carrying such loads. This maneuvering capability is obtained by providing attitude stabilization and a six-degrees-of-freedom reaction control system.

Two such devices were studied in detail under the recently completed Contract NAS8-20316, entitled Definition of Experiment Program in Space Operations, Techniques and Subsystems (Independent Manned Manipulator - IMM), Reference (1). One such device, the Maneuvering Work Platform (MWP), shown in Figure 1, is an early availability concept consisting of an open structure, which is operated by a pressure-suited astronaut. This concept is essentially a maneuverable workshop, with self-contained power, propulsion, attitude stabilization, and environmental control/life support system. It carries a full complement of tools and spare parts for orbital servicing and maintaining of other vehicles. The second, more advanced concept, shown in Figure 2, is the Space Taxi, which features complete, environmentally controlled encapsulation of the astronaut. The latter provides the capability of performing maintenance tasks in a shirt-sleeve environment by means of bi-lateral master-slave manipulators controlled from within the pressurized cabin. Both of these small utility spacecraft embody remotely operated grapplers or master-slave manipulators, controllable by the crewman, for docking and anchoring his vehicle to various cooperative and uncooperative space objects.

During this study MSD-T advanced the concept of a simplified electromechanical docking and anchoring manipulator employing astronaut rate and acceleration commands to position the six-degrees-of-freedom manipulator arm, as well as to control the opening of the attachment tongs.

The flight maneuvers of the IMM vehicles are also controllable in six degrees of freedom by the astronaut. The similarity in commanded degrees of freedom led to a unique control concept which was developed for the Maneuvering Work Platform, wherein a single set of controls could be selectively shared to provide both vehicle and manipulator commands. The single control station provides position control of both vehicle and manipulator with the left hand and attitude control of both with the right. A selector switch on the left hand controller provides a simple means for simultaneously

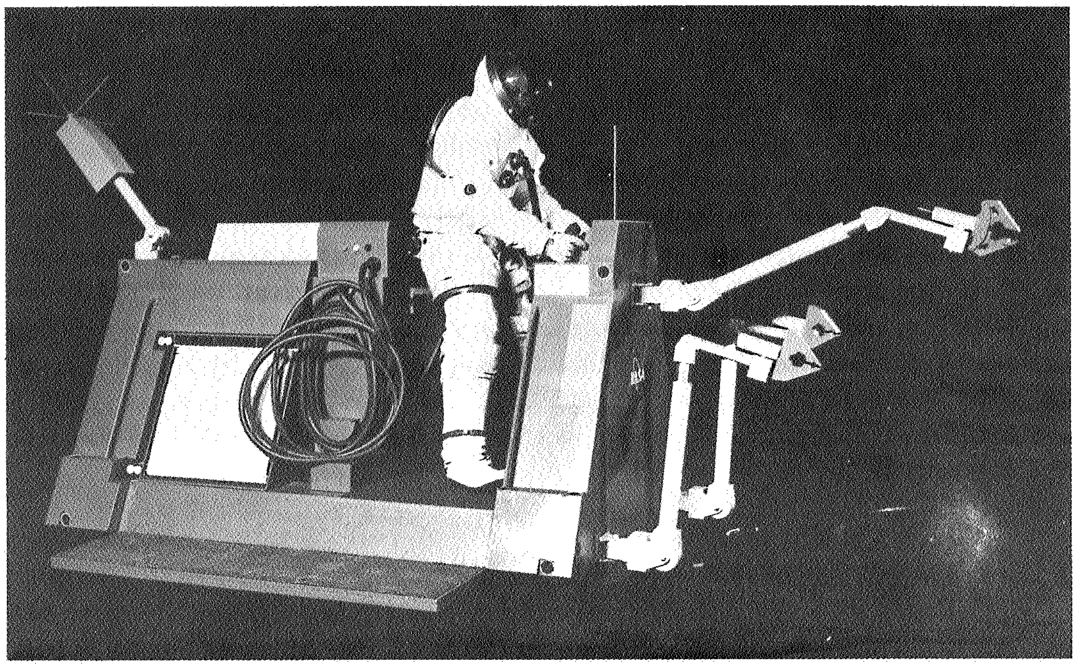


Figure 1 - Full Scale Mockup of Maneuvering Work Platform (MWP) with Anchoring Manipulators Extended

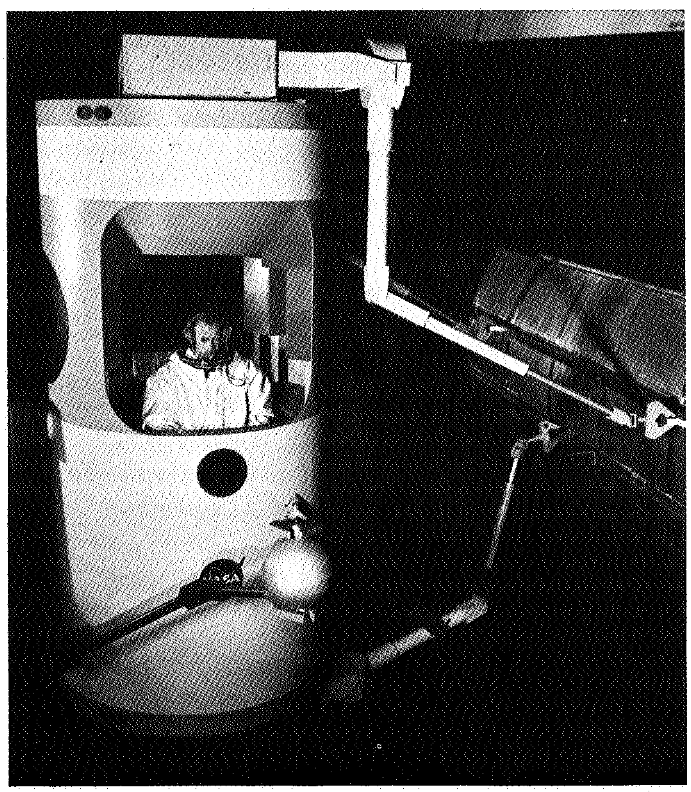


Figure 2 - Full Scale Mockup of Space Taxi Anchored to Simulated Worksite

switching the command signals from both controllers to either the vehicle or the manipulator.

Due to the long lead time required for design and development of space-type manipulators (identified during the foregoing study as a critical area of technology deficiency), and because of the large impact upon vehicle configuration and system integration requirements imposed by manipulator and controller concepts, the current contract was awarded. Special emphasis during the performance of this contract has been placed upon the design, prototype development and testing, under simulated mission conditions, of a rate command docking and anchoring manipulator, in order to validate the controller/manipulator concept and to evaluate the ability of the astronaut to perform the required tasks with the simplified controllers.

The tests conducted as a part of this program were highly successful, and all test objectives were achieved. The validity of the controller/manipulator concept was verified, and the versatility of the rate command grappling device was demonstrated.

This document is the final report on the subject program and contains a discussion of the design and development of the system, a description of the system and its testing, and a presentation of the test results. Conclusions are drawn and recommendations for future work in this field are made.

2.0 OBJECTIVE AND SCOPE

2.1 OBJECTIVES

The objectives of this program as set forth in Reference (2) are as follows:

a. Design and breadboard an experimental version of the rate command grappling manipulator, based upon the design concept for the Maneuvering Work Platform (MWP) as discussed in Section **3.0.**

b. Design and breadboard the control station provisions for the selectively shared controller concept designed for the MWP.

c. Conduct manned testing utilizing frictionless platform facilities capable of adequately simulating relative vehicle-to-worksite motions, in order to accomplish the following:

   (1) Evaluation of an experimental version of a rate command grappling manipulator to verify the versatility of the overall mechanism in accomplishing representative docking, grappling and anchoring functions.

   (2) Evaluation of the control concept and of the feasibility of a shared control station in which the vehicle and the manipulator are each controlled in six degrees of freedom by selective use of one set of controllers.

2.2 SCOPE

This research program is a task addendum to Contract NAS8-20316, entitled Definition of Experiment Program in Space Operations, Techniques and Subsystems. The contract covers a six and one-half month period of technical performance.

The limited period for performance of this program, together with the program cost limitation, necessitated careful management of engineering and manufacturing man hours and schedules, as well as of material dollars and procurement lead time. Selection and specifications for purchased material was expedited and advanced procurement lists were prepared.

Throughout the design, procurement and fabrication phases, weekly status meetings were held by the Project Engineer to maintain a running status of man-hours, schedules and parts fabrication or procurement. Close in-house control of parts and materials was maintained throughout.

The accelerated completion of the manipulator and controller module permitted early preliminary evaluation of system operation, revealing some deficiencies in operating loads and rates which in turn led to a number of design modifications.

3.0 DESCRIPTION OF SHARED COMMAND CONTROL SYSTEM CONCEPT FOR MANIPULATOR AND VEHICLE

3.1 VEHICLE CONTROL CONCEPT

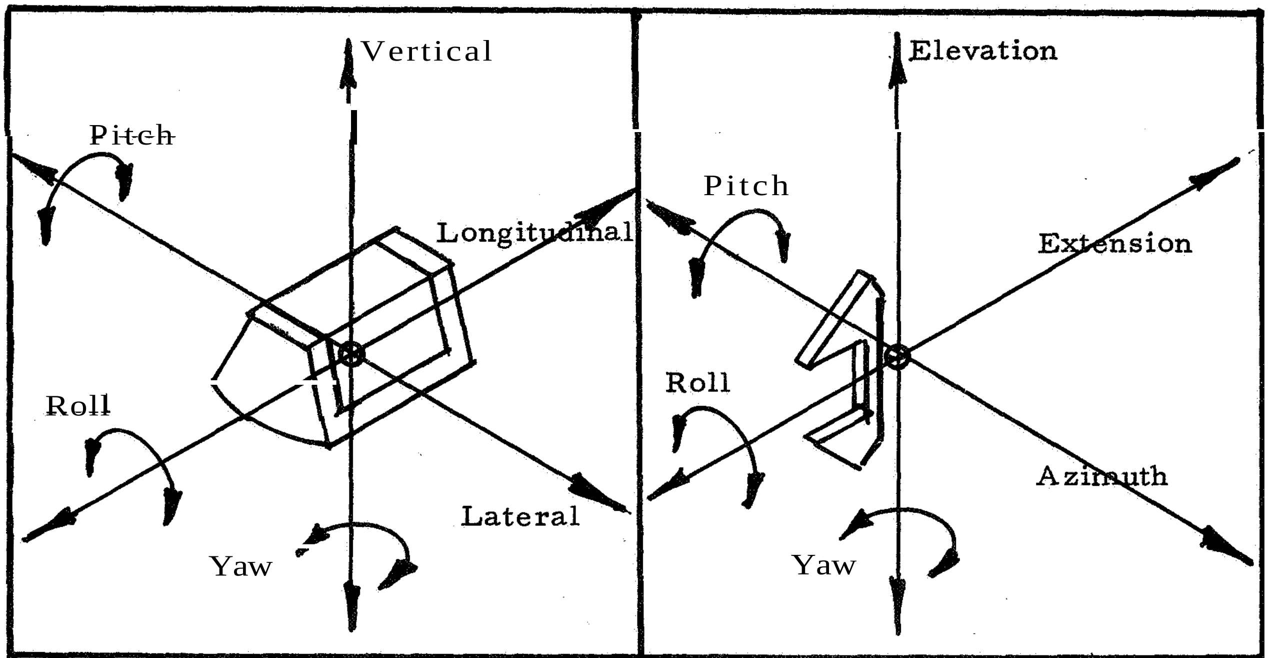
For maximum maneuverability in space, the Maneuvering Work Platform (MWP) contains a flight control system designed to provide the astronaut with control provisions (1) for altering the vehicle position by directing translation along the vertical, longitudinal and transverse axes, and (2) for commanding changes in vehicle attitude by rotation in pitch, roll and yaw. The six degrees of vehicle control freedom are illustrated in Table I below. All vehicle maneuvers are achieved by appropriate commands to twenty-four reaction control thrusters acting either symmetrically for translations or asymmetrically for vehicle rotations. The arrangement of the thrusters on the vehicle is such that all control forces surround the vehicle center of gravity, with all rotational torques applied as pure control couples. Detailed discussion of this vehicle is contained in Reference (1).

The control electronics system for the MWP accepts rate and acceleration commands from the astronaut, accepts vehicle motion data from system sensors, selects the torques required to bring vehicle motion into agreement with astronaut commands, and causes these torques to be applied to the vehicle by firing the appropriate reaction control thrusters. As a result the MWP is a vehicle with good handling qualities and automatic attitude stabilization in the absence of operator commands.

3.2 MANIPULATOR CONTROL CONCEPT

The MWP is equipped with grappling devices by means of which the astronaut can, at will, anchor to and release his vehicle from both co-operative and non-cooperative orbiting objects. The grappler control requirements for docking and anchoring are similar to those for control of the vehicle, in that the position and attitude of the gripping tongs must be maneuvered by commands from the astronaut. It is recognized that the application of bi-lateral master-slave manipulators to MWP docking and anchoring might offer potential advantages in natural position control, force feedback and greater dexterity. These advantages would be obtained at the expense of additional MWP weight, volume, cost and complexity. Details of such expenses can be obtained from the section of Reference (1) which is devoted to the Space Taxi. Results of preliminary design studies by MSD-T indicate that a non-bi-lateral, rate command docking and anchoring manipulator will provide the astronaut with six degrees of control of the manipulator similar to the flight control for the MWP vehicle. Table I compares the manipulator and vehicle control motions.

TABLE I MWP/MANIPULATOR DEGREES OF CONTROL FREEDOM



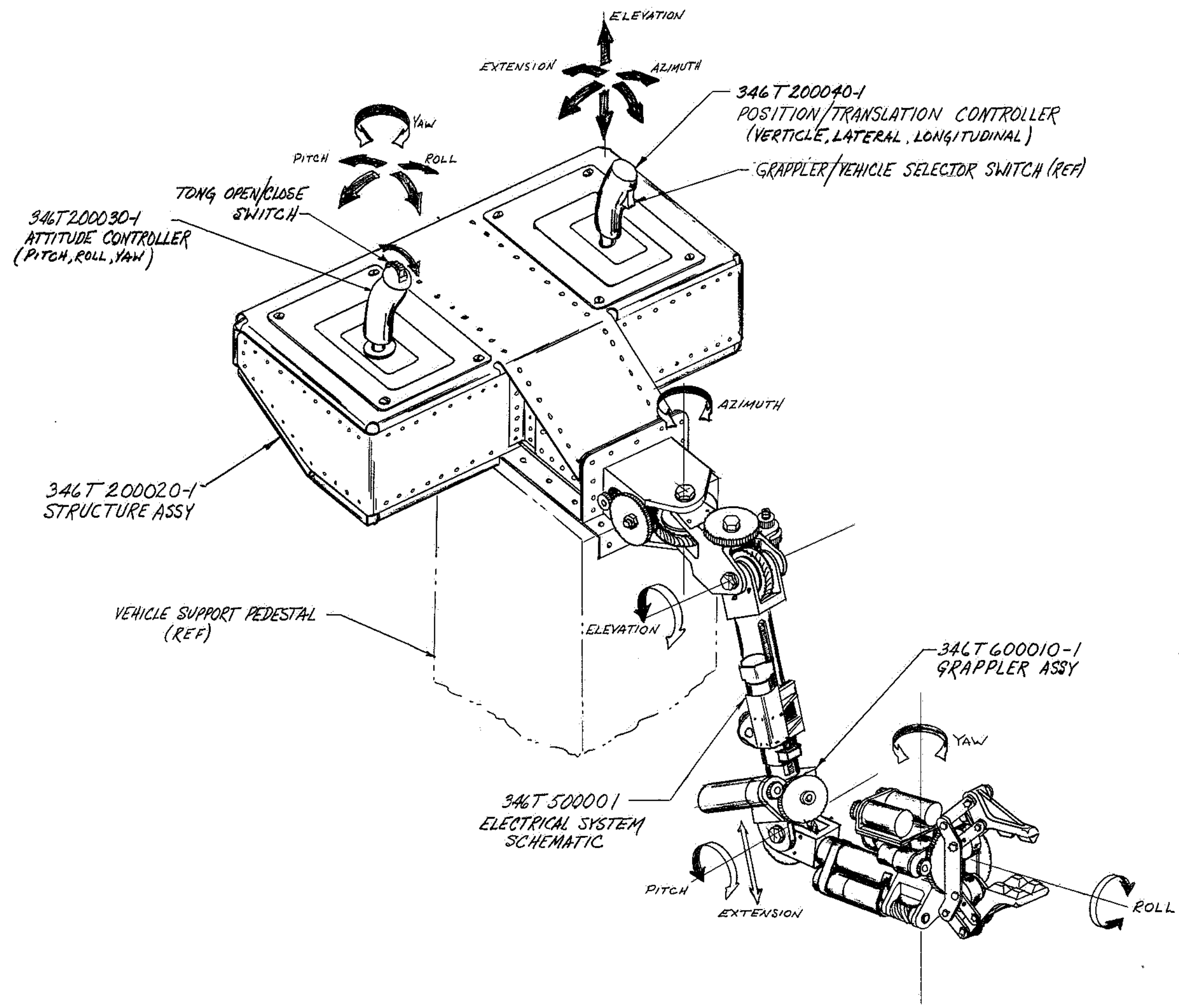
MWP VEHICLE		MANIPULATOR
1. Up/Down 2. Left/Right 3. Fore/Aft	Translation or Position Commands	1. Elevation 2. Azimuth 3. Extension
4. Pitch 5. Roll 6. Yaw	Attitude or Orientation Commands	4. Pitch 5. Roll 6. Yaw
		7. Tongs Open/Close

3.3 SHARED CONTROL CONCEPT

Unlike the crew stations of conventional spacecraft or aircraft which surround the crewman, the Maneuvering Work Platform has only a minimal control station, permitting maximum mobility and ease of ingress and egress. Due to this fact and in view of the obvious parallel between the vehicle flight commands and the positioning and attitude commands to the docking grappler, maximum functional integration has been achieved by combining control utilization into a single set of controllers for selective command of either vehicle or grappler motions. The functions of this integrated control station are shown in Figure 3.

Translation control of the vehicle is unaugmented by any form of synthetic feedback or closed loop assist. Attitude control of the MWP, on

REVISIONS				
SYM	ZONE	DESCRIPTION	DATE	APPROVED
A		UPDATED PICTURE TO SHOW LATEST CONFIGURATION	5/30/67	W.C. BOYCE



NOTES: 1. FOR BASIC DATA & SCOOTER TESTBED GEOMETRY SEE 346T 010001

FIG 3

TITLE	APPROVAL	DATE	MISSILES AND SPACE DIVISION LTV AEROSPACE CORPORATION P.O. BOX 6267 DALLAS TEXAS 75222
PROJECT	W.C. Boyce	3/4/67	MODULE ASSY IMM PROTOTYPE GRAPPLER MANIPULATOR & CONTROLLER
CHK BY			
DRAWN BY	L.C. BOKER	3/1/67	SIZE A4 · CODE IDENT NO. 11813 · 346T010010
CUSTOMER			

346T010010

the other hand, is augmented by a gyro sensor equipped stabilization system which provides automatic attitude stabilization, attitude hold, and attitude rate control proportional to control deflection.

Proportional attitude rate command is also utilized for control of the attitude commands for the manipulator, but positional commands for the manipulator, like those for vehicle translation, are simple acceleration on/off commands.

Instantaneous changeover from grappler control to flight control is accomplished by merely releasing a spring-loaded trigger switch on the left hand controller. By virtue of the MWP automatic stabilization system, vehicle attitude is maintained during manipulator operation. Conversely, the manipulator maintains any commanded position relative to the MWP whenever system commands revert to vehicle control.

4.0 DESIGN REQUIREMENTS

4.1 ASSUMPTIONS AND GUIDE LINES

4.1.1 DERIVATION AND RATIONALE FOR CRITERIA

Inasmuch as this program is intended to evaluate the feasibility of a shared-function rate command docking manipulator, as proposed for the Maneuvering Work Platform (MWP), the performance characteristics and related design criteria generated for the MWP have been used in establishing design requirements for the prototype grappler. These criteria are based upon the missions and mission profiles defined and analyzed in reference (1). The design criteria for the prototype system are listed in paragraph 4. 1. 2. Where feasible the criteria for design of the prototype are derived directly from the following list of criteria for the space-operational system, although a number of deviations were made in the interest of expediency. The following paragraphs list the basic design data for the Space Version of the MWP Docking Manipulators, from which the criteria in paragraph 4. 1. 2 were derived.

a. The grapplers shall be electrically actuated by means of Discrete Controllers providing on-off rate commands. "On" commands will be momentary.

b. No force or position feedback shall be provided.

c. The MWP will have four docking and anchoring grapplers: Three on the forward module and one on the aft module. All grapplers will be identical.

d. In performing docking maneuvers, it is assumed that only one grappler will be operated at a time, except for gross slewing motions, which may be commanded simultaneously.

e. One set of controllers shall actuate all grapplers as commanded by a grappler selector switch, which enables one grappler to be controlled at a time.

f. After selection of a second grappler, a brake shall be applied to the first grappler which locks it in the position it had at the time of re-selection. Grappler motion brakes shall require power only during application or release.

g. It shall be possible to release brakes without actuation of the grapplers, thus allowing the MWP to be rotated at the worksite by means of the MWP reaction control thrusters. This permits the MWP to anchor with one grappler, then pivot about this attachment to orient the vehicle for

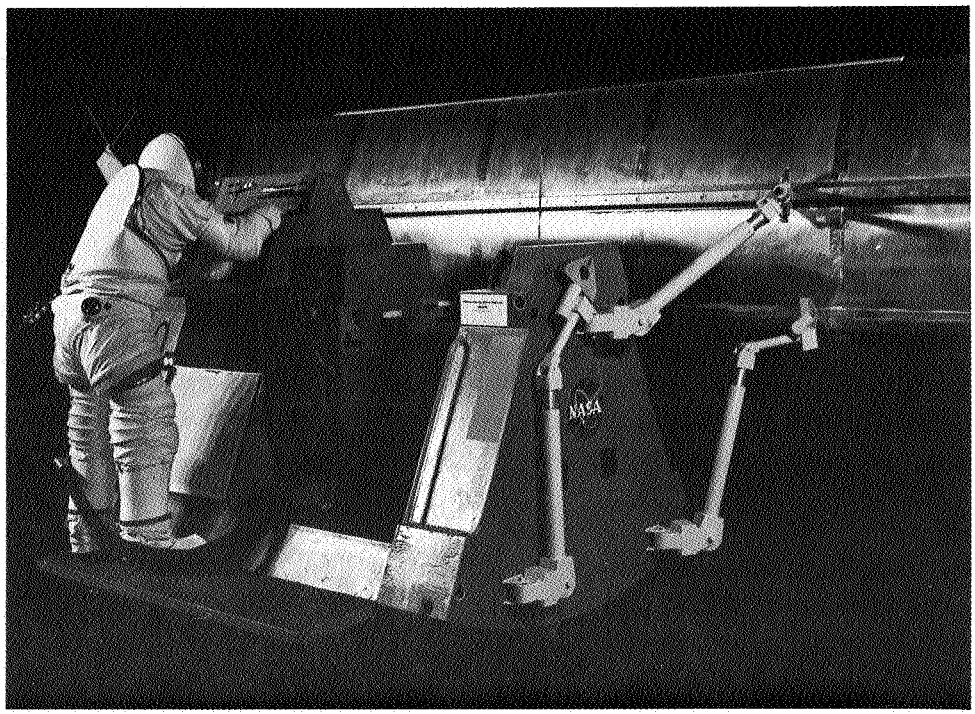


Figure 4 - Mockup of Maneuvering **Work** Platform Anchored to Worksite with Crewman Preparing to Perform Maintenance Task

attachment of other grapplers. Figure 4 shows a full scale mockup of the MWP anchored to a simulated worksite while the crewman prepares to perform a maintenance task.

h. Control motions shall be oriented in the same sense as those for the MWP flight control system. The left hand controller will control gross motions of the grappler arm, and the right hand controller will control the more precise motions of the grappler wrist and hand. Arm motions are elevation (up/down), azimuth (right/left) and extension (extend/retract). These correspond to MWP Translation motions (up/down, right/left and fore/aft). Wrist motions are pitch, roll and yaw, the same as MWP attitude motions.

i. **A** single mode selector switch will be provided to enable both controllers to be simultaneously switched to command either MWP or grappler. This switch shall be spring-loaded to the MWP control position.

j. In addition to the tong open/close switch there shall also be an emergency switch permitting simultaneous release of all tongs.

k. Control motions are sense-oriented to the motions of the forward grapplers. The aft grappler, therefore moves in an opposite sense. Furthermore, due to the large excursions of the arms, to achieve front docking, bottom docking, and port and starboard side docking, some out-of-phase motion of the forward grapplers relative to the controls may occur.

It is presently believed that this condition can be overcome through learning, and no complex control logic is envisioned.

l. A single rate of motion (to be determined) is presently envisioned for the gross motions of the grapplers. However, a hi/low rate capability may later prove desirable. It also appears desirable to provide variable rates for finer control in the MWP Flight Control System, and this same feature will undoubtedly also be applied to the grapplers.

m. The necessity for shock absorption and the suitability of brakes or slip clutches at the pivot points to absorb collision forces shall be given consideration, in order to avoid damage to the grapplers or the "target" vehicle.

n. The operational grapplers will be designed to exert a steady state maximum force of 25 lb (111.2 N) measured either axially or transversely.

o. It is assumed that closing (or separation) rates of the MWP and the "target" vehicle are matched within 0.5 fps (0.15 mps), and 3 deg per sec (.05 radians per sec) angularly.

p. The mass of the MWP shall be limiting in establishing arrestment forces.

q. Inasmuch as the MWP will be used in support LEM Lab, Apollo CSM and the S-IVB Workshop, the tongs portion shall be configured for the following:

- 1 1/2 in (3.8 cm) dia. ball, similar to a trailer hitch. This may be furnished in the form of an adapter which can be mounted either adhesively or mechanically to otherwise smooth surfaces around the Pallet anchoring area.

- 1 1/2 in (3.8 cm) dia. tubing such as might be found in structural trusses in the S-IVB Workshop airlock, area, or used as handrails on the CSM.

- Standard machined or sheet metal structural shapes and thicknesses such as flanges, angles, channels and brackets varying from 0.06 in (0.15 cm) to 3.0 in (7.62 cm) such as may exist in the region of the J-2 Propellant Utilization Valve.

r. Further consideration should be given to the requirement for, and feasibility of, adjusting the gripping force, in order to avoid damage.

s. No power shall be required to maintain the grip closed.

4.1.2 DESIGN CRITERIA FOR PROTOTYPE DOCKING MANIPULATOR

The following criteria, derived primarily from the foregoing, have been used in the design of the prototype grappler. Some concessions have been made in consideration of the one-G test environment to prevent the manipulator from becoming too massive. For example, the steady state force capability of the grappler has been reduced to 10 lb (44.5 N) measured either axially or transversely. In addition, the ability to release brakes without actuation of the grapplers, thus allowing the MWP to be rotated at the work site by means of the MWP reaction control thrusters has been omitted. This capability was intended to permit the MWP to anchor with one grappler, then pivot about this attachment to orient the vehicle for attachment of other grapplers. Inasmuch as the test vehicle has only one grappler, and since this feature would have added considerably to the cost and complexity of the system, it was deleted. The prototype grappler design criteria are as follows:

a. The grapplers shall be electrically actuated by means of controllers providing on-off command for fixed arm rate and rate proportional wrist commands.

b. No mechanical force or position feedback shall be provided.

c. The manipulator shall lock in the position it had at the time of command release. The manipulator arm and wrist motions shall require power only during application.

d. Control motions shall be oriented in the same sense as those for the MWP Flight Control System. The left hand controller will control the gross position of the grappler arm and the right hand controller will control the attitude of the grappler wrist, and tong opening. Arm motions are elevation (up/down), azimuth (right/left) and extension (extend/retract). These correspond to MWP translation motions (up/down, right/left and fore/aft). Wrist motions are pitch, roll and yaw, the same as MWP attitude motions.

e. A selector switch will be provided to enable the controllers to command either MWP or grappler. This switch will be spring-loaded to return to the MWP vehicle control position when released.

f. A switch for commanding tong open/close shall be provided. A tong closure force of 25 lb (111.2 N) shall be provided. No power will be required to maintain the grip closed.

g. A single rate of motion is envisioned for gross motions of the grappler arm. A high/low gain selector switch shall be provided, allowing this rate to be experimentally varied between 5 and 10 deg per sec (0.09 and 0.18 radians per sec).

The grappler wrist motions will be rate proportional to controller deflection, with a maximum rate of 10 deg per sec (0. 18 radians per sec).

h. The grapplers will be designed to exert a steady state maximum force of 10 lb (44. 5 N) measured either axially or transversely.

i. A generalized, all-purpose tong configuration shall be used which permits anchoring to the following:

° 1 1/2 in (3.8 cm) dia. ball, similar to a trailer hitch.

° 1 1/2 in (3.8 cm) dia. tubing.

° Standard machined or sheet metal structural shapes and thicknesses.

j. Limit switches shall be provided to interrupt the power of the actuating motors in order to electrically limit arm motions prior to actual mechanical interference. This is to preclude jamming and/or damage to the mechanism.

4. 1. 3 No shock absorption shall be provided but the design shall include adjustable overload clutches to minimize damage due to collision. Inasmuch as the greatest moments occur at the elevation and azimuth pivots, clutches shall be provided at these points. An additional clutch shall be provided in the extension drive train to protect this mechanism in the event of a head-on collision. Clutches shall be adjusted to release when a force of approximately 10 lb (44. 5 N) is exerted either axially or transversely at the fully extended manipulator tongs.

4. 2 DESIGN PHILOSOPHY

The design of any article is governed by factors other than the absolute performance criteria. It is the "philosophy" used during the design which dictates how the criteria are to be met. This attitude can have a major influence upon the cost of the final article and the delivery schedules, as well as upon the appearance and function of the device. The design philosophy for the MWP prototype docking grappler is discussed in three categories.

4. 2. 1 "PROOF OF PRINCIPAL" BREADBOARD vs. "FINAL" CONFIGURATION

The stated objectives of this program dictate an experimental or "breadboard" approach to the hardware as opposed to "flight" configurations. This approach permits a degree of flexibility, in that motors, gear trains, etc. , may be left exposed rather than hidden, thus enabling relatively easy alteration if necessary. This approach "paid off" on the current contract, inasmuch as several gear train alterations and motor substitutions were required to obtain the desired performance.

4.2.2 COMPONENT SELECTION CRITERIA

The scope of the current program dictated selection of components which were essentially "off-the-shelf". The six month program which encompassed design, vendor procurement, fabrication, assembly and test did not permit optimization of design nor of component selection. Most components were selected directly from vendor catalogues with only secondary regard to weight. Low cost and a minimum of lead time outweighed such niceties as appearance or "qualified" hardware status. While weight was given some consideration, the low cost and ready availability of "stock" gears lead to their selection. Inasmuch as system optimization was not attempted, the "brute force" approach was sometimes taken if it simplified fabrication or saved procurement lead time.

4.2.3 RELAXATION OF RIGID SPECIFICATION AND QUALITY CONTROL

In the interest of economy, since the experimental grappler was to be used under predictable laboratory conditions and since no safety of flight is involved, some relaxation of material and process standards, as well as rigid inspection and quality control requirements was permitted. Extensive use of tooling materials was made, since these were readily available in-house. The materials used consisted almost entirely of 6061 T6 aluminum and 4130 and 4340 steel. Material callouts on the drawings gave the basic material and specification, but were qualified by the phrase "tooling stock acceptable". This means that while the material meets commerical standards, it does not necessarily comply with the certification and more rigid aerospace material standards. In most cases weldments were not reheat treated, inasmuch as they are substantially over-designed. Where material finish was critical from the standpoint of fit or function, or from the standpoint of abrasion resistance or appearance, aluminum parts were anodized and steel parts cadmium plated. In some cases aluminum parts were treated with a brush coat of Alodine to expedite processing.

The "fit and function" philosophy of inspection was adopted in lieu of 100 percent inspection of detail parts, thus permitting more leeway on nom-critical dimensions. Following the fit and function philosophy, parts were deliberately designed for shimming on assembly where feasible, and slotted holes are used for adjustment in a number of instances, thus reducing the need for expensive jigbore operations.

5.0 CONFIGURATION DESIGN

5.1 OVERALL SYSTEM

Figure 5 is a photograph showing the overall test system, This system is comprised of a Manipulator/Controller Module, the hydrazine-propelled test vehicle upon which it is mounted, and the electrical power supplies for operating the manipulator and the vehicle. The basic geometry of the test system is presented in Figure 6, and the various elements which comprise the system are discussed separately under the following headings. The measured angles and rates of motion obtainable with the prototype manipulator are contained in Table 11.

5.2 MECHANICAL SYSTEM

Functionally, the grappler can be subdivided into two segments, comparable to the upper and lower portions of the human arm. The upper arm segment, the "position" of which is controlled by the left hand controller, which also controls the translation or "position" of the vehicle in space, and a lower arm segment whose "attitude" is controlled by the right hand controller. The right hand controller is also used to control the "attitude" or orientation of the vehicle. In this manner, corresponding translational motions of the vehicle and of the upper arm (elevation = vehicle vertical translation; azimuth = vehicle lateral translation; and extension = vehicle longitudinal translation) are controlled by the position controller. The attitude controller commands vehicle and "wrist" yaw, vehicle and "wrist" roll, and vehicle and "wrist" pitch. The control pedestal also provides the structural support for the "shoulder" pivots which constitute the upper end of the manipulator arm, and also contains the azimuth pivot and drive train. (Refer to Figure 8).

The upper arm assembly is supported from the controller pedestal as shown in Figure 7. It is comprised of an azimuth trunnion, (346T600060-23 Fitting) an elevating upper arm housing (346T600060-3 Weld Assembly), and an

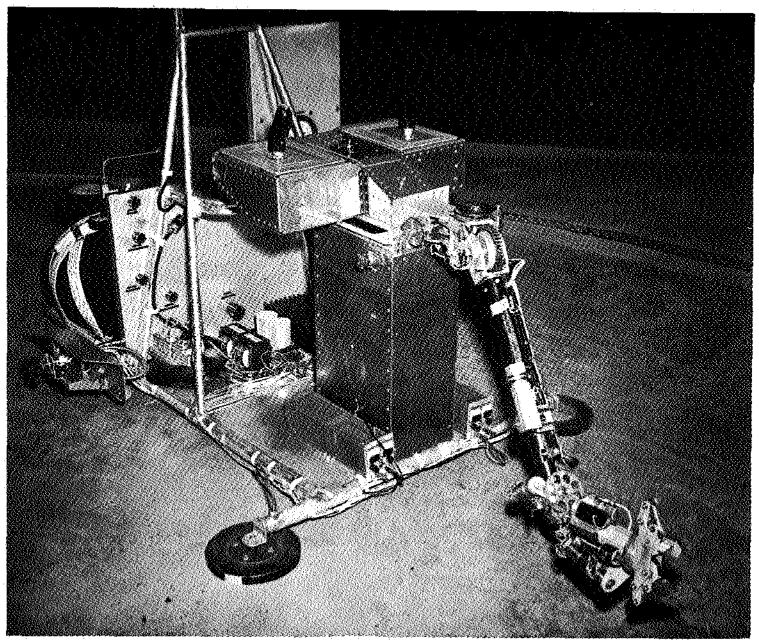
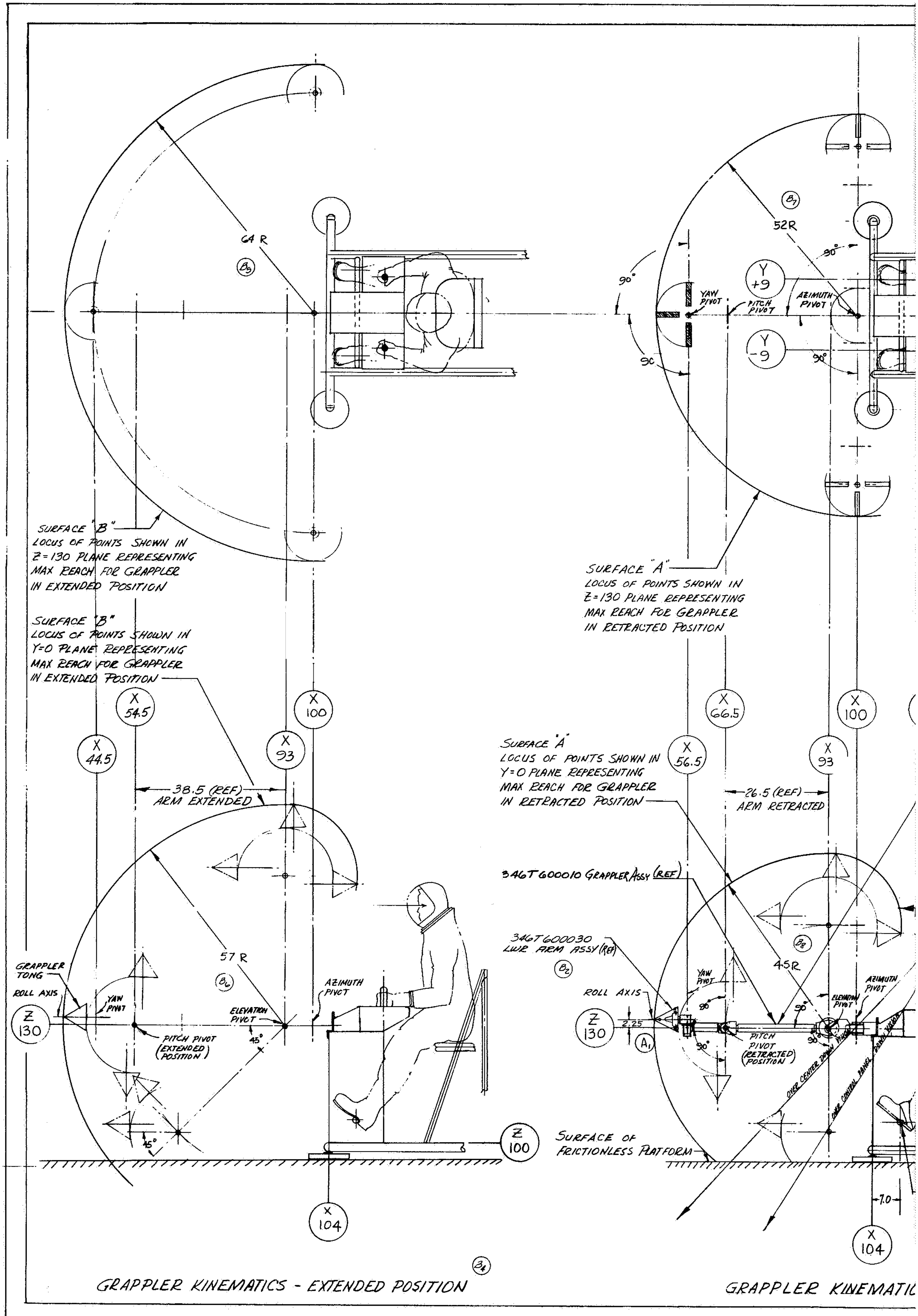
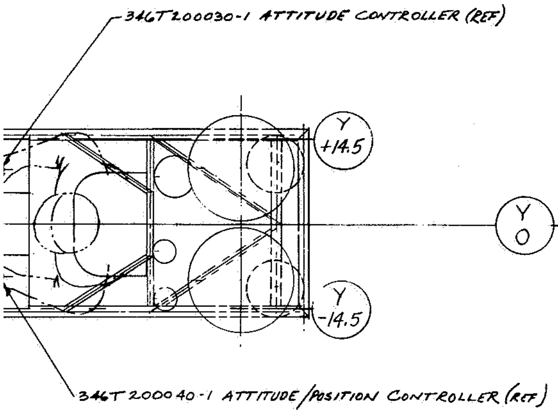


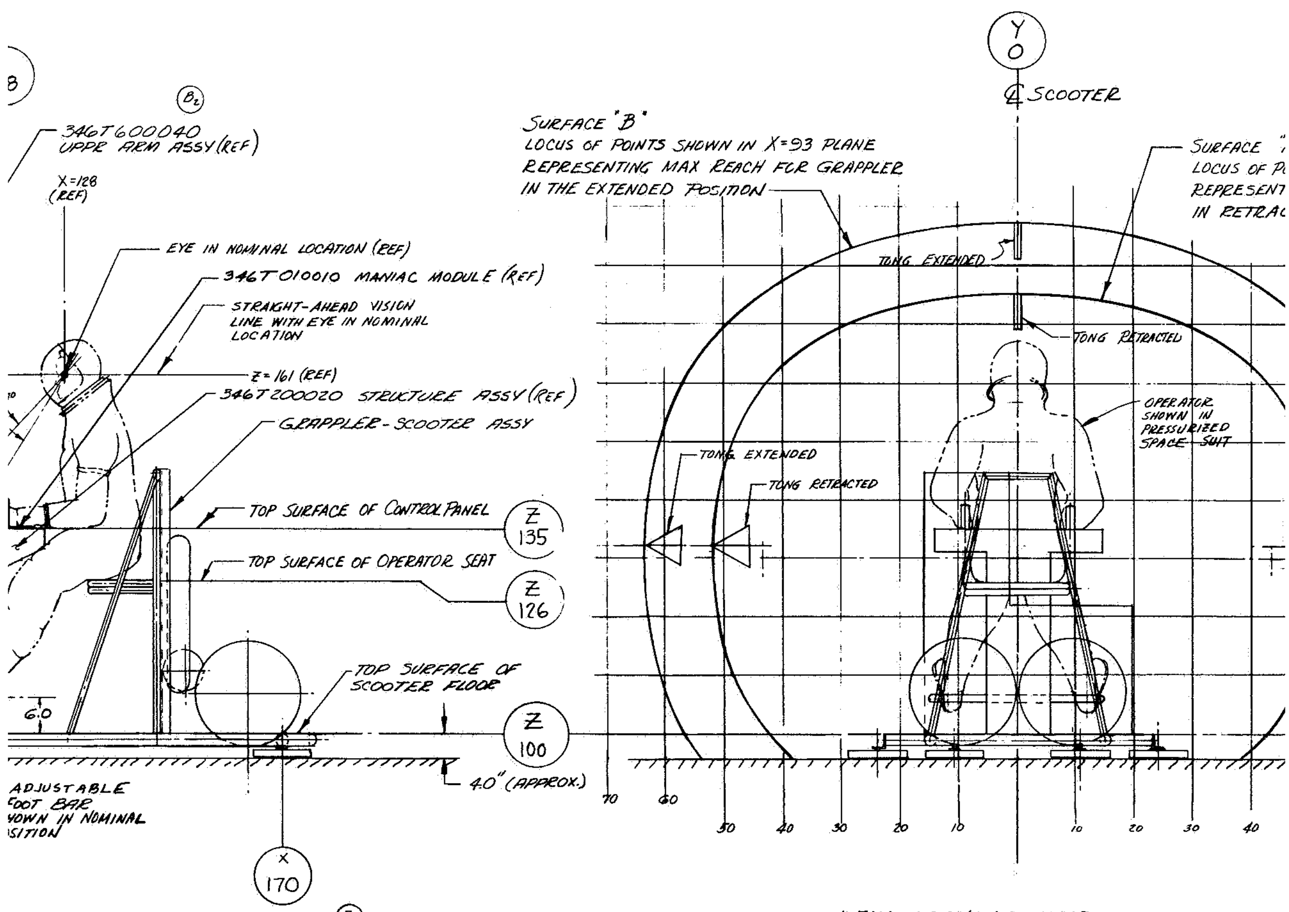
Figure 5 - Manipulator Test System Showing Manipulator/Controller Module Mounted on Hydrazine-Propelled Air-Bearing Test Vehicle



GRAPPLER KINEMATICS - EXTENDED POSITION

GRAPPLER KINEMATIC





- RETRACTED POSITION

VIEW LOOKING FWD
GRAPPLER IN RETRACTED & EXTENDED POSITIO

REVISION A

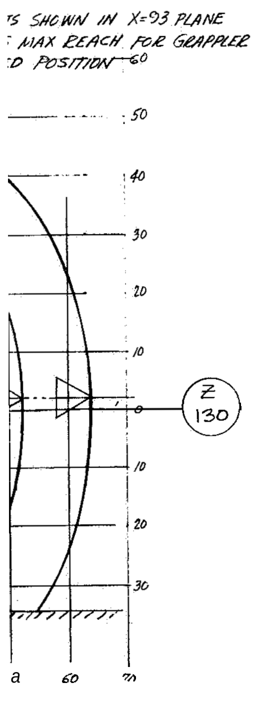
1. CHANGED ROLL AXIS OFF-SET DIMENSION FROM 2.00 INCHES TO 2.25 INCHES

REV B

1. REVISED REAR VIEW TO ADD SCOOTER & CHANGE LOCUS OF POINTS TO AGREE WITH OTHER VIEWS.
2. ADD 346T600030 & 346T600040 TO FD
3. REVISED SIDE VIEW COMPLETELY (ADDED SCOOTER, LWR & UPPR ARM ASSYS)
4. REVISED SIDE VIEW TO ADD SCOOTER
5. CHANGED RADIUS (WAS 63R)
6. CHANGED RADIUS (WAS 56R)
7. CHANGED RADIUS (WAS 51R)
8. CHANGED RADIUS (WAS 44R)

NOTE:

1. DATA CONTAINED IN THIS DWG TO BE USED IN THE DESIGN OF THE PROPULSIVE/SCOOTER TEST VEHICLE AND IS NOT TO BE USED FOR FABRICATION OF EITHER THE IMM PROTOTYPE GRAPPLER/CONTROL MODULE OR THE SCOOTER.



(B)

FIGURE 6

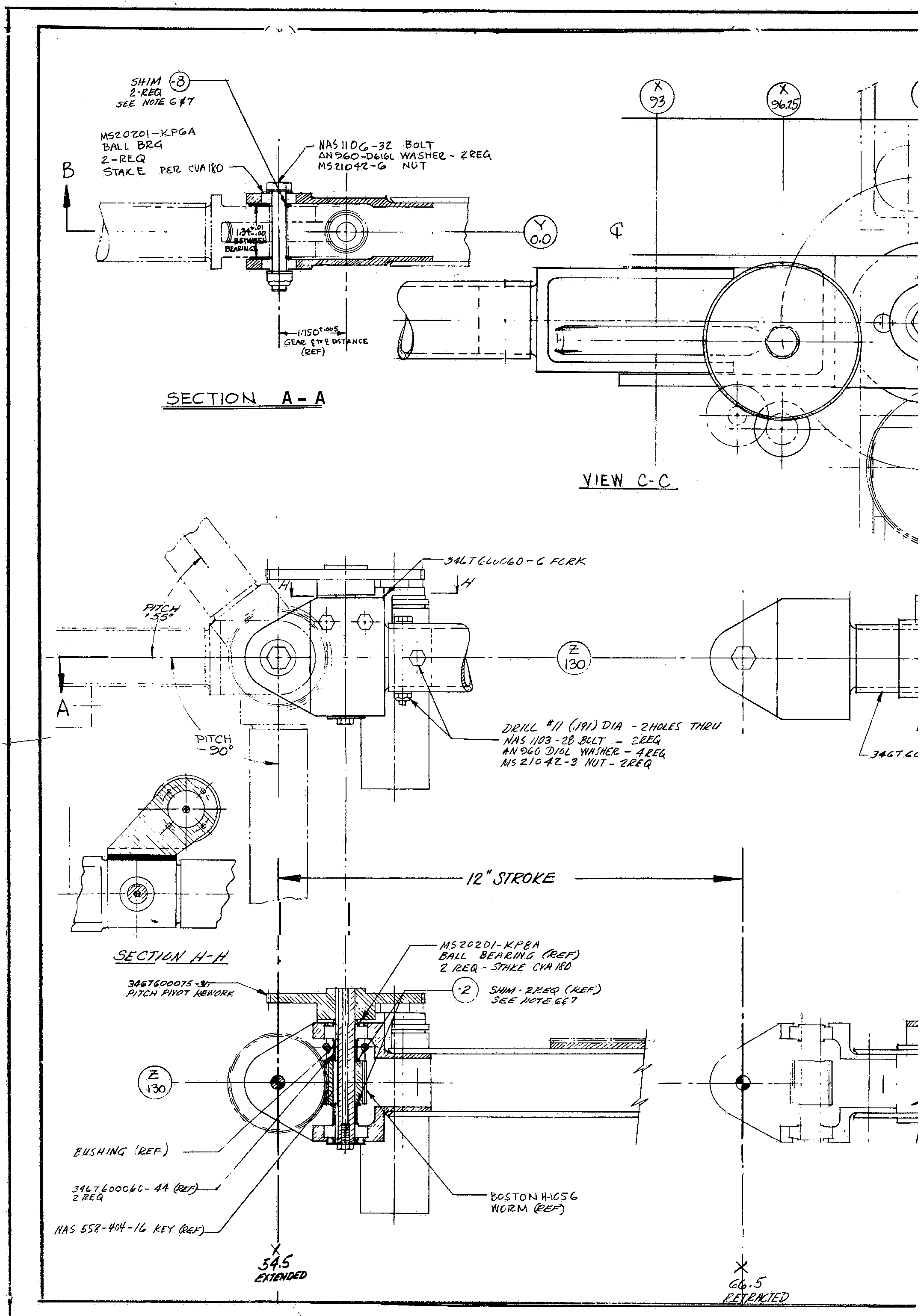
TITLE	APPROVAL	DATE
PROJECT	WCBoyce	1-17-67
PROJ	WCBoyce	3/10/67
DN BY	Colleoni	3/3/67
B REVISION		
PROJ	WCBoyce	12/30/66
CHK BY		
DRAWN BY	MATZA	12-30-66
CUSTOMER		
CONTRACT NO. NAS 8-21024		

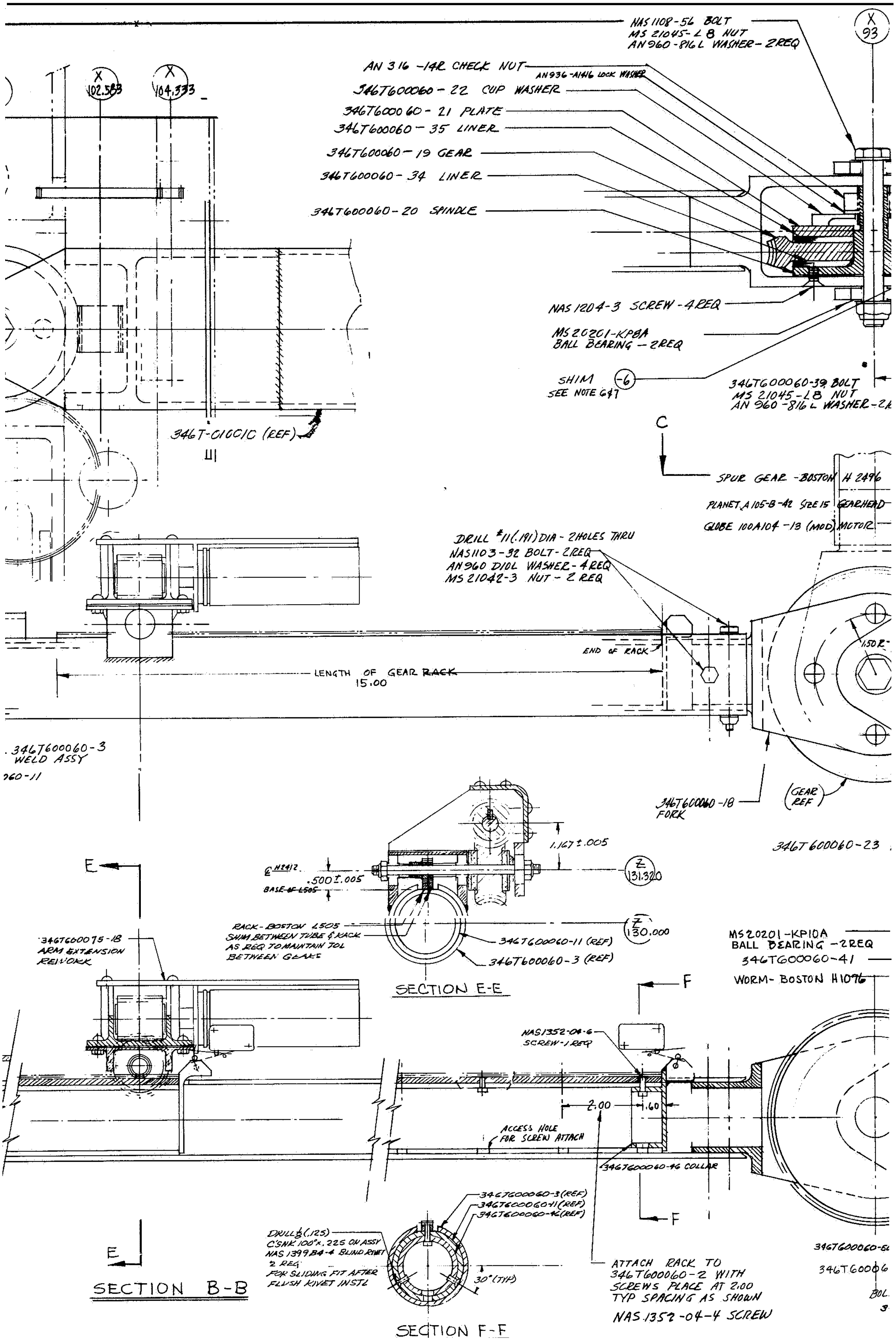
LTV ASTRONAUTICS DIVISION
LTV AEROSPACE CORPORATION
PO BOX 6267 DALLAS TEXAS 75222

SCOOTER ASSY
IMM PROTOTYPE DEMONSTRATOR
(GRAPPLER & CONTROL BASIC DATA)

SIZE 34 x 77 | CODE IDENT NO. 11813 | 346T-010001

SCALE | REV LTR B | SHEET 1 OF 1


SHIM (-8) 2-REQ SEE NOTE 6 & 7
MS20201-KP6A BALL BRG 2-REQ STAKE PER CVA180
NAS 1106-32 BOLT
AN960-D616L WASHER - 2REQ
MS21042-6 NUT
B
Y 0.0
1.750±.005 GEAR ℄ TO ℄ DISTANCE (REF)
SECTION A-A
X 93
X 96.25
VIEW C-C
346T600060-6 FORK
PITCH +55°
H
A
PITCH -90°
Z 130
DRILL #11 (.191) DIA - 2HOLES THRU
NAS 1103-28 BOLT - 2REQ
AN960 D10L WASHER - 4REQ
MS21042-3 NUT - 2REQ
SECTION H-H
12" STROKE
MS20201-KP8A BALL BEARING (REF) 2 REQ - STAKE CVA 180
346T600075-30 PITCH PIVOT REWORK
(-2) SHIM - 2REQ (REF) SEE NOTE 6 & 7
BUSHING (REF)
346T600060-44 (REF) 2 REQ
NAS 558-404-16 KEY (REF)
BOSTON H-1056 WORM (REF)
X 54.5 EXTENDED
X 66.5 RETRACTED



X 93
NAS 1108-56 BOLT
MS 21045-L8 NUT
AN960-816L WASHER-2REQ
X 102.583
X 104.333
AN 316 -14R CHECK NUT
AN936-A1416 LOCK WASHER
346T600060-22 CUP WASHER
346T600060-21 PLATE
346T600060-35 LINER
346T600060-19 GEAR
346T600060-34 LINER
346T600060-20 SPINDLE
NAS 1204-3 SCREW-4REQ
MS 20201-KP8A
BALL BEARING-2REQ
SHIM -6
SEE NOTE 6&7
346T600060-39 BOLT
MS 21045-L8 NUT
AN 960-816L WASHER-2
346T-010C10 (REF)
C
SPUR GEAR -BOSTON H 2496
PLANET A 105-B-42 SIZE 15 GEARHEAD
GLOBE 100A104-13 (MOD) MOTOR
DRILL #11(.191) DIA - 2HOLES THRU
NAS1103-32 BOLT-2REQ
AN960 D10L WASHER-4REQ
MS 21042-3 NUT-2 REQ
END OF RACK
LENGTH OF GEAR RACK
15.00
1.50 R
346T600060-3
WELD ASSY
060-11
346T600060-18
FORK
GEAR REF
1.167 ±.005
346T600060-23
E
℄ H2412
.500 ±.005
BASE OF L505
Z 131.320
RACK-BOSTON L505
SHIM BETWEEN TUBE & RACK AS REQ TO MAINTAIN TOL BETWEEN GEARS
Z 130.000
346T600060-11 (REF)
346T600060-3 (REF)
SECTION E-E
346T600075-18
ARM EXTENSION
REWORK
MS20201-KP10A
BALL BEARING -2REQ
346T600060-41
WORM- BOSTON H1076
F
NAS1352-04-6
SCREW-1 REQ
2.00
.60
ACCESS HOLE
FOR SCREW ATTACH
346T600060-46 COLLAR
346T600060-3(REF)
346T600060-41(REF)
346T600060-46(REF)
F
DRILL 1/8(.125)
C'SNK 100°x.225 ON ASSY
NAS 1399B4-4 BLIND RIVET
2 REQ
FOR SLIDING FIT AFTER
FLUSH RIVET INSTL
30° (TYP)
ATTACH RACK TO
346T600060-2 WITH
SCREWS PLACE AT 2.00
TYP SPACING AS SHOWN
NAS 1352-04-4 SCREW
346T600060-
346T6000
E
SECTION B-B
SECTION F-F

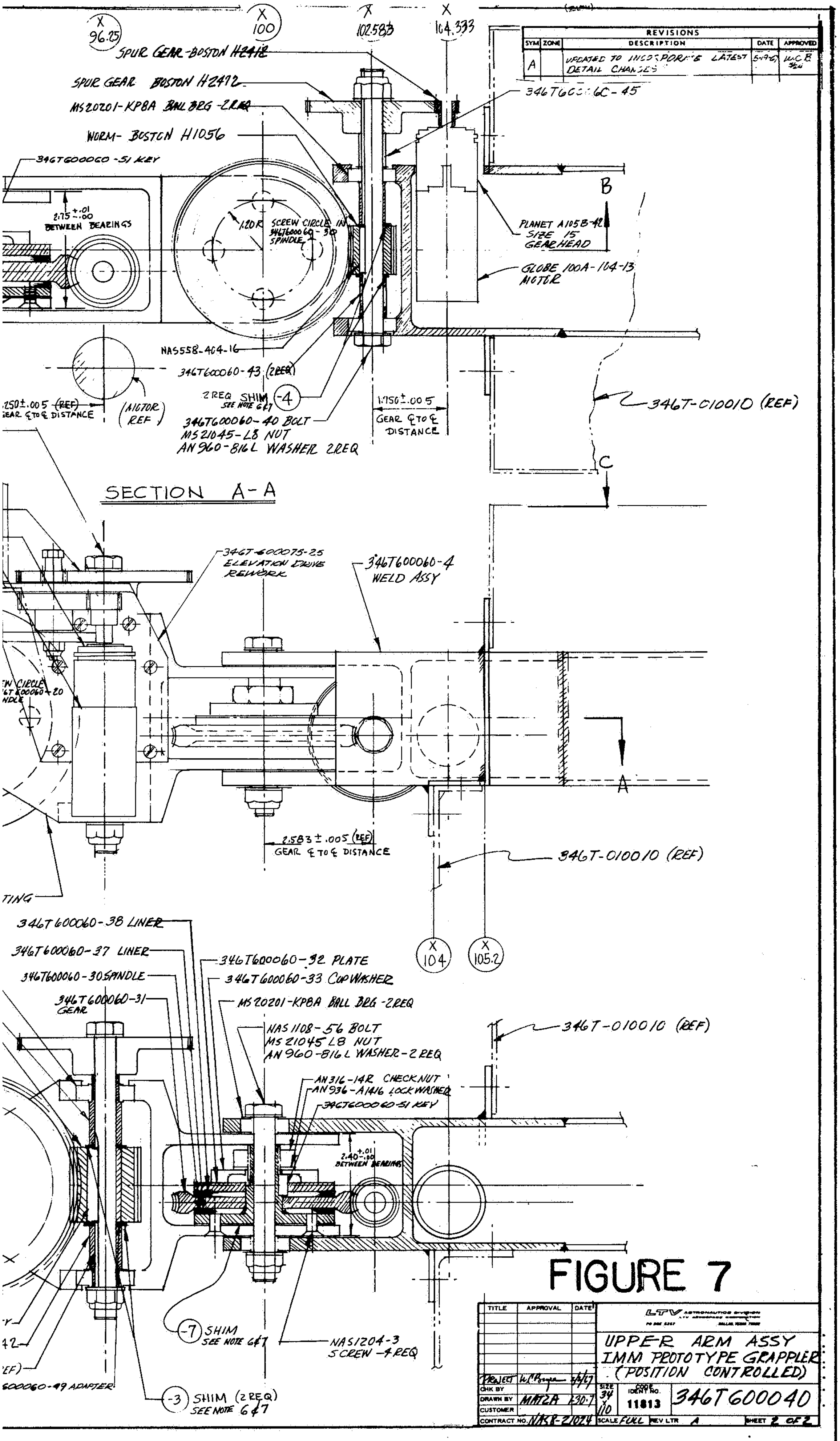

REVISIONS
SYM | ZONE | DESCRIPTION | DATE | APPROVED
A | UPDATED TO INCORPORATE LATEST DETAIL CHANGES
X 96.25
X 100
X 102.583
X 104.333
SPUR GEAR-BOSTON H2412
SPUR GEAR BOSTON H2412
MS20201-KPBA BALL BRG -2REQ
WORM- BOSTON H1056
346T600060-51 KEY
2.75 +.01 -.00 BETWEEN BEARINGS
1.20R SCREW CIRCLE IN 346T600060-30 SPINDLE
PLANET A105B-42 SIZE 15 GEARHEAD
GLOBE 100A-104-13 MOTOR
B
NAS558-404-16
346T600060-43 (2REQ)
2REQ SHIM SEE NOTE 6&7
-4
1.750±.005 GEAR ℄ TO ℄ DISTANCE
346T600060-40 BOLT
MS21045-L8 NUT
AN960-816L WASHER 2REQ
(MOTOR REF)
346T-010010 (REF)
C
SECTION A-A
346T-600075-25 ELEVATION DRIVE REWORK
346T600060-4 WELD ASSY
A
2.583±.005 (REF) GEAR ℄ TO ℄ DISTANCE
346T-010010 (REF)
X 104
X 105.2
346T600060-38 LINER
346T600060-37 LINER
346T600060-30 SPINDLE
346T600060-31 GEAR
346T600060-32 PLATE
346T600060-33 CUP WASHER
MS20201-KPBA BALL BRG -2REQ
NAS1108-56 BOLT
MS21045 L8 NUT
AN960-816L WASHER-2REQ
346T-010010 (REF)
AN316-14R CHECKNUT
AN936-A1416 LOCKWASHER
346T600060-51 KEY
2.40 +.01 -.00 BETWEEN BEARINGS
-7 SHIM SEE NOTE 6&7
NAS1204-3 SCREW -4REQ
600060-49 ADAPTER
-3 SHIM (2REQ) SEE NOTE 6&7
LTV ASTRONAUTICS DIVISION
UPPER ARM ASSY
IMM PROTOTYPE GRAPPLER
(POSITION CONTROLLED)
TITLE | APPROVAL | DATE
DRAWN BY MAIZA
CONTRACT NO. NAS8-21024
SIZE 34 10
CODE IDENT NO. 11813
346T600040
SCALE FULL
REV LTR A
SHEET 2 OF 2

FIGURE 7

TABLE II MEASURED MOTIONS AND RATES OF MOTION MEASURED ON IMM PROTOTYPE DOCKING MANIPULATOR

FUNCTION	MOTION	GAIN (4)	TIME, SEC. (1) (2)	RATE (1) (2)
ELEVATION (3)	145° (+85/-60)	HIGH	UP 24 DN 17	5.7°/sec 7.7°/sec
		LOW	UP (Stall) DN 21	--- 6 4°/sec
AZIMUTH	180°(± 90°)	HIGH LOW	15 19	12°/sec 9.5°/sec
EXTENSION	11 in (27.94 cm)	---	2.5	4.5 in/sec (11.4 cm/sec)
PITCH	145° (+60°/-85°)	MAX	14.5	10°/sec
ROLL	Unlimited	MAX	14.5 (for 360°)	25°/sec
YAW	170° (±85°)	MAX	10	17°/sec
TONGS	3.25 in (8.3 cm) (max open to full close)	---	0.5	6.5 in/sec (16.5 cm/sec)

Notes:
1. Times and rates measured to no load.
2. Times and rates are averaged for right and left, extend and retract, etc.
3. Times and rates for elevation are not averaged because of considerable differences due to gravity.
4. High - low gain change effective only on azimuth and elevation. "Max" shown for pitch, roll and yaw indicates maximum modulation.

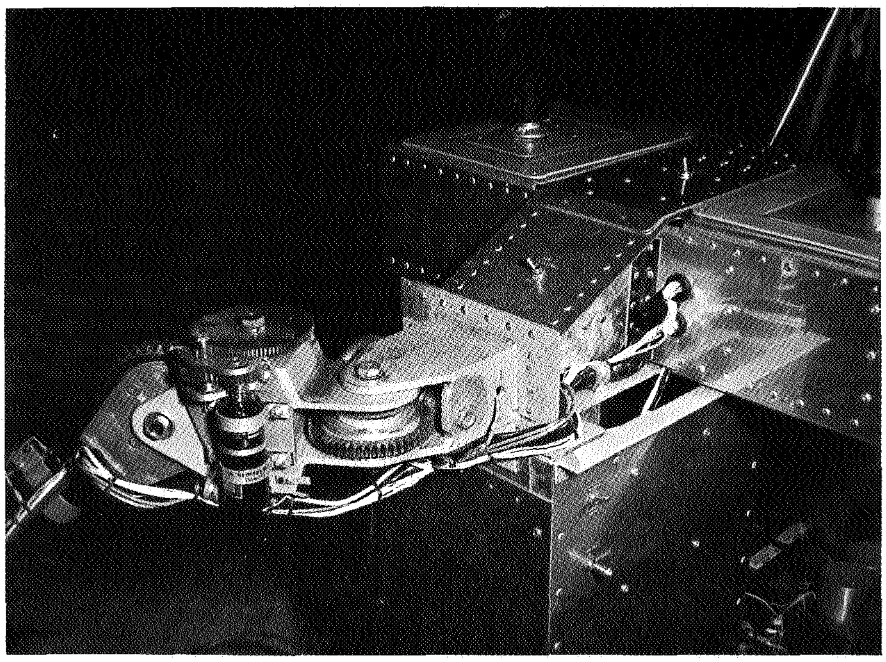


Figure 8 - Manipulator/Controller Support Pedestal Showing Azimuth and Elevation Pivots and Related Drive Mechanisms

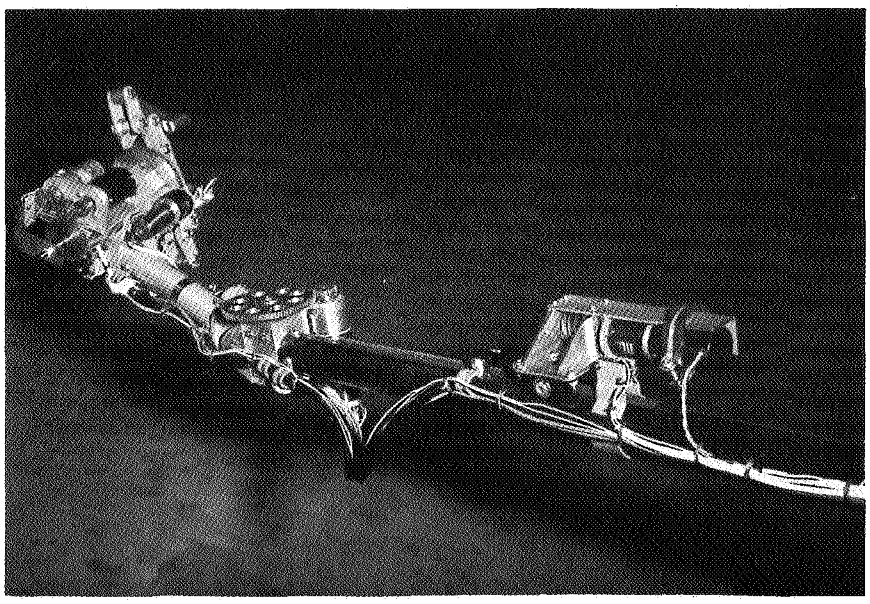


Figure 9 - Manipulator Arm Showing Extension Drive (Right), Pitch Pivot (Left Center), and Wrist Assembly at Left

extensible tubular member (346T600060-11) also Figure 9 which contains the "elbow" (or pitch pivot). Each of the upper arm motions is driven by identical 50 volt DC motors, working through multi-stage drive trains consisting of spur gearing and worm gearing. Each of these drive trains is protected by an adjustable friction clutch from damage due to overload. Figure 13 shows the basic data for the manipulator arm, listing all motors and gear ratios.

The three position drive motors, whose stall torque is rated at 14 oz-in (0.099 N-m), operate through integral gearheads with an internal ratio of 11.73: 1. The azimuth drive is further geared down by a 6: 1 external spur gear pair which drives a 50: 1 worm/worm gear combination to position the entire arm approximately 90 deg right and left from "neutral".

The elevation pivot is at the outboard end of the azimuth trunnion, and the elevation drive train is housed within this trunnion, as shown in Figure 8. On the elevation drive, the output of the integral motor gearhead is geared down 320: 1 via an 8: 1 spur gear train which drives a 40: 1 worm/worm gear assembly. Under normal operation this is the most heavily loaded drive train since it must work against the component of gravity, although potentially higher gear tooth loads can be developed in the azimuth drive train due to the greater moment arm from the end of the tong to the azimuth pivot. The clutches at both azimuth and elevation pivots should therefore be adjusted to slip at approximately 10 lb (44.5 N) applied laterally at the tongs, thus limiting the moments at these pivots to 630 and 560 lb-in (71.6 and 63. 8 N-m) respectively.

Suspended from the azimuth trunnion at the elevation pivot is the telescoping portion of the upper arm. It is comprised of a large fork, bolted to the upper end of the tubular housing which is slotted to accommodate the rack on the internally extensible member. The outer housing has two welded structural "bridges" to prevent deformation of the slot and to support the extension drive train. The lower end of the extensible member terminates in a bolted on fork which contains the pitch pivot.

The extension drive gearhead and motor rotate a 4:1 worm/wheel pair directly. Due to differing pitch diameters a further reduction of 2.67: 1 takes place between the worm gear and the pinion which moves the rack causing arm extension. A slip clutch has been interposed between the rack drive pinion and the 4 tooth worm gear to prevent overload due to axially applied collision forces. This friction clutch should also be adjusted to slip at approximately 10 lb (44. 5 N) applied axially.

At the outboard end of the upper arm is the pivot and drive train for operation of the lower arm, whose motions are controlled by the attitude controller. This pivot, see Figure 10, designated the "pitch" pivot, may be likened to the elbow on the human arm. It is driven through an angular range of 145 deg by a 115 volt 400 cps AC servo motor with integral gear

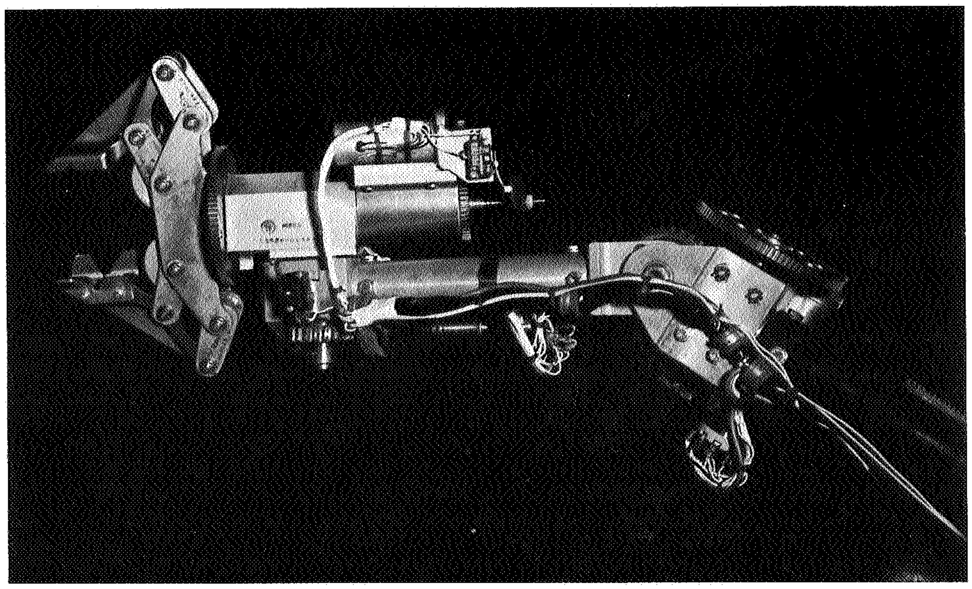


Figure 10 - Manipulator Lower Arm and Wrist. Tongs drive motors (Top) Drive Ball Bearing Screw on Axis of Roll Rotation.

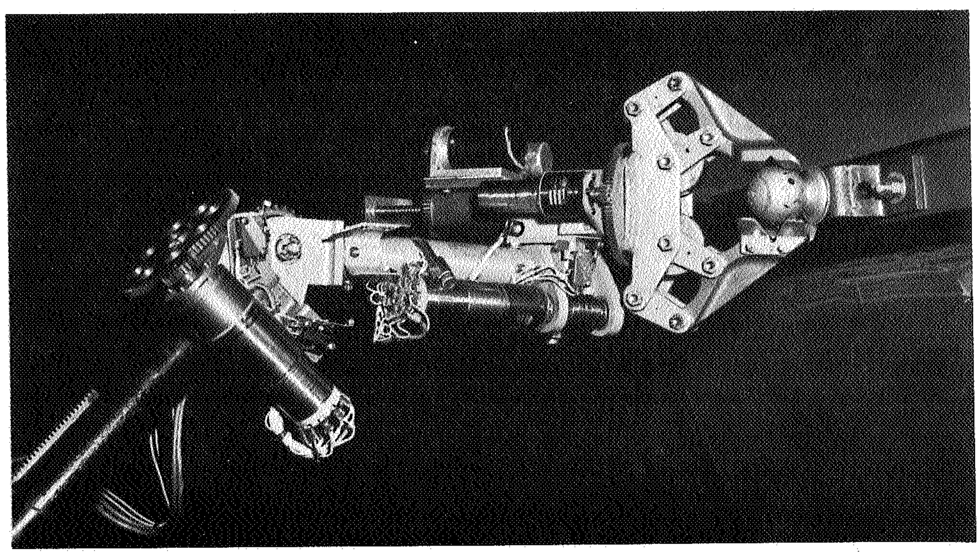


Figure 11 - Manipulator Tongs and Lower Arm Shown Anchored to Ball on Docking Target. Visible are Pitch Drive (Left) Yaw Drive (Lower Center), Roll Drive (Center), and Tongs Drive (Upper Center)

train and tachometer generator. The integral gearhead, whose ratio is 49: 1, is coupled with a 4 1 external spur gear train which in turn rotates a 30: 1 worm and worm-wheel combination.

The inboard portion of the lower arm is comprised of a tubular "fore arm", pivoting at the "elbow" at the upper end and containing the "yaw" pivot housing and drive train at the lower end as shown in Figure 10. Yaw rotation is obtained by a 115 volt 400 cps AC servo motor with a 77. 5: 1 integral worm gear is mounted on the yaw spindle causing the wrist to rotate approximately 90 deg either side of neutral.

That portion of the lower arm which rotates at the yaw pivot (see Figures 10 and 11) is a complex, multi-functioned assembly. The two-piece housing supports the drive trains for both the roll and the gripping function of the tongs, as well as serving as a bearing housing for roll rotation, see Figures 14 and 15. The large diameter bearings in the roll housing permit the the grip to be actuated by axial motion of a ball bearing screw along the roll axis. This screw is driven at the aft end by rotation of the ball bearing nut through a spur gear train. This 3:1 gear train is powered by two 27 volt DC motors, working in tandem. One with a rated stall torque of 3.4 oz-in (. 024 N-m) has an integral electromagnetic brake, while the other motor, rated at 18 oe-in (. 125 N-m) stall torque, has none. The brake is provided to hold the tongs at any selected grip opening without application of electrical power. The brake is disengaged whenever motor power is applied.

The tongs consist of two jaw members constrained to parallel motion of all times by four-bar linkages supported from the rolling portion of the "wrist". The jaws are biased to the open position by a pair of NEG'ATOR* springs operating on symmetrical drives attached to the linkage. The jaws are closed by pulling on the free ends of the NEG'ATORS along the roll axis of the "wrist". Inasmuch as the tongs comprise the rolling portion of the assembly, and the grip drive train is mounted on the non-rotating roll housing, a swivelling connection is required in the grip-drive mechanism to prevent actuation of the grip when the wrist is rolled. This is accomplished by mounting a small swivel inside the roll housing, at the forward end of the ball bearing screw, which is prevented from rotating by keying the swivel housing to the non-rotating outer portion of the roll housing, allowing it only to slide in and out as the ball screw is driven axially in the housing. The forward end of the swivel is pinned to a slide block which actuates the NEG'ATOR springs. This block is keyed to the rolling portion of the wrist and allowed to move only axially.

The rolling portion of the grip has unlimited rotation, and is driven by a 115 volt 400 cps AC servo motor with a rated stall torque of 55 oz-in (. 382 N-m). This motor has an integral gearhead with an internal ratio of 165.96: 1, which in turn drives an 8: 1 external spur gear pair to cause roll.

* NEG'ATOR is a copyright name for a patented non-cumulative force spring manufactured by the Hunter Spring Co.

The three attitude control drive motors are configured as rate servos with drive rates proportional to control displacement, thus permitting fine attitude control modulation. Grip actuation, like the upper arm drives, is a simple on-off function, but relatively fine grip opening is obtainable by momentary actuation of the control switch.

Inasmuch as the Maneuvering Work Platform, for which this is intended to be an experimental prototype, was envisioned for use in support of the LEM Lab, the Apollo CSM and the S-IVB Workshop, the tongs have been configured for general purpose docking to a variety of objects which might be encountered in these space systems. Since a spherical object can be approached from any side through a wide range of angles, the tongs were configured to grasp a 1 7/8 in (4.77 cm) diameter standard trailer hitch ball. The configuration permits attaching to the ball either head-on, or from above and below, or from either side. In addition, since considerable use of tubular construction is envisioned in space, the tongs are also designed to anchor to tubular members, as well as standard sheet metal or machined structural shape and thicknesses such as flanges, angles, channels and brackets ranging from paper thickness up to approximately 3 in (7.62 cm). Figure 12 shows a view over the operator's shoulder showing the manipulator anchored to the ball mounted on the Sixth Degree of Freedom Test Frame (See Section

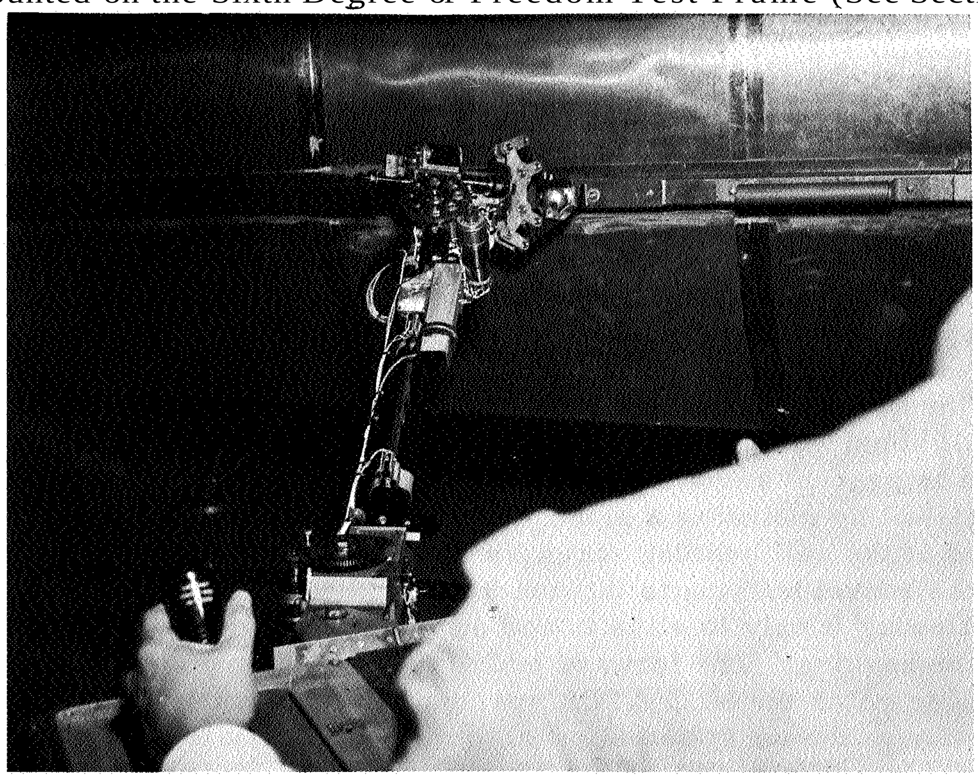
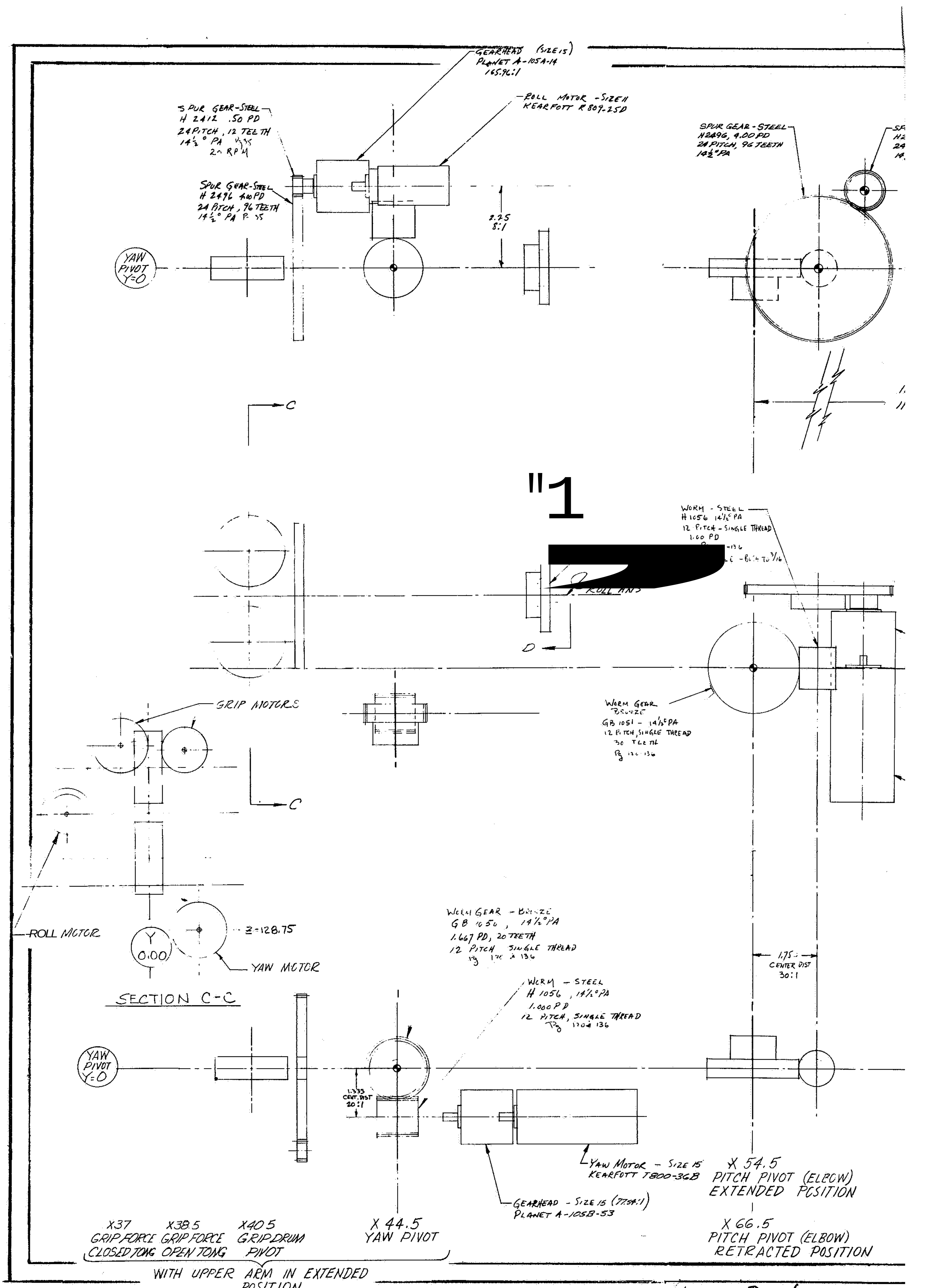
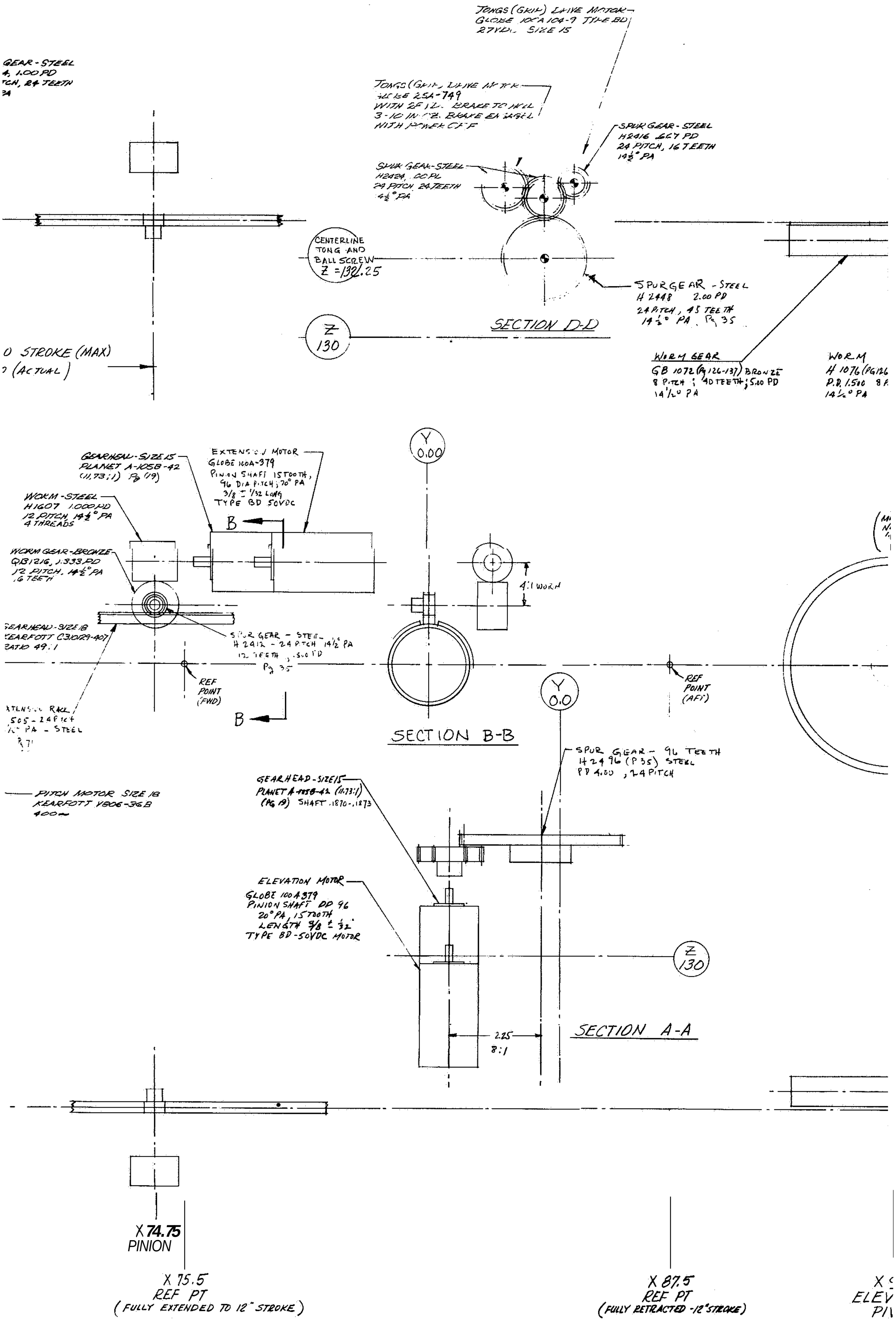


Figure 12 - View from Operators Station Showing Manipulator Anchored to Ball on Simulated Worksite. Position Controller in Foreground Controls Gross Position of Arm


GEARHEAD (SIZE 15)
PLANET A-105A-14
165.96:1
ROLL MOTOR - SIZE 11
KEARFOTT R 809-25D
SPUR GEAR-STEEL
H 2412 .50 PD
24 PITCH, 12 TEETH
14½° PA
SPUR GEAR-STEEL
H 2496 4.00 PD
24 PITCH, 96 TEETH
14½° PA
2.25
8:1
YAW PIVOT Y=0
SPUR GEAR-STEEL
H2496, 4.00 PD
24 PITCH, 96 TEETH
14½° PA
C
WORM - STEEL
H 1056 14½° PA
12 PITCH - SINGLE THREAD
1.00 PD
D
WORM GEAR BRONZE
GB 1051 - 14½° PA
12 PITCH, SINGLE THREAD
30 TEETH
GRIP MOTORS
C
ROLL MOTOR
Y 0.00
Z=128.75
YAW MOTOR
SECTION C-C
WORM GEAR - BRONZE
GB 1050, 14½° PA
1.667 PD, 20 TEETH
12 PITCH SINGLE THREAD
1.75
CENTER DIST
30:1
WORM - STEEL
H 1056, 14½° PA
1.000 PD
12 PITCH, SINGLE THREAD
YAW PIVOT Y=0
1.333
CENT. DIST
20:1
YAW MOTOR - SIZE 15
KEARFOTT T800-36B
GEARHEAD - SIZE 15 (77.54:1)
PLANET A-105B-53
X 54.5
PITCH PIVOT (ELBOW)
EXTENDED POSITION
X37
GRIP FORCE
CLOSED TONG
X38.5
GRIP FORCE
OPEN TONG
X40.5
GRIP DRUM
PIVOT
X 44.5
YAW PIVOT
WITH UPPER ARM IN EXTENDED POSITION
X 66.5
PITCH PIVOT (ELBOW)
RETRACTED POSITION



TONGS (GRIP) DRIVE MOTOR— GLOBE 10CA104-9 TYPE BD 27VDC SIZE 15
TONGS (GRIP) DRIVE MOTOR GLOBE 25A-749 WITH 2F 12 BRAKE TO HOLD 3-10 IN OZ. BRAKE ENGAGED WITH POWER OFF
GEAR - STEEL 4, 1.00 PD PITCH, 24 TEETH PA
SPUR GEAR - STEEL H2416 .667 PD 24 PITCH, 16 TEETH 14½° PA
SPUR GEAR-STEEL H2424, 1.00 PD 24 PITCH, 24 TEETH 14½° PA
CENTERLINE TONG AND BALL SCREW Z = 132.25
SPURGEAR - STEEL H 2448 2.00 PD 24 PITCH, 48 TEETH 14½° PA, Pg 35
SECTION D-D
Z 130
D STROKE (MAX)
(ACTUAL)
WORM GEAR GB 1072 (Pg 126-137) BRONZE 8 PITCH ; 40 TEETH ; 5.00 PD 14½° PA
WORM H 1076 (PG126 P.D. 1.500 8 P 14½° PA
GEARHEAD - SIZE 15 PLANET A-1058-42 (11.73:1) Pg 19
EXTENSION MOTOR GLOBE 100A-379 PINION SHAFT 15 TOOTH, 96 DIA PITCH; 20° PA 3/8 ± 1/32 LONG TYPE BD 50VDC
Y 0.00
WORM - STEEL H1607 1.000 PD 12 PITCH, 14½° PA 4 THREADS
B
WORM GEAR - BRONZE - QB1216, 1.333 PD 12 PITCH, 14½° PA 16 TEETH
4:1 WORM
GEARHEAD - SIZE 18 KEARFOTT C310129-407 RATIO 49:1
SPUR GEAR - STEEL H 2412 - 24 PITCH 14½° PA 12 TEETH, .500 PD Pg 35
REF POINT (FWD)
REF POINT (AFT)
Y 0.0
EXTENSION RACK 505 - 24 PITCH PA - STEEL
SECTION B-B
SPUR GEAR - 96 TEETH H2496 (P35) STEEL PD 4.00, 24 PITCH
PITCH MOTOR SIZE 18 KEARFOTT Y806-36B 400~
GEARHEAD - SIZE 15 PLANET A-1058-42 (11.73:1) (PG 19) SHAFT .1870-.1873
ELEVATION MOTOR GLOBE 100A379 PINION SHAFT DP 96 20° PA, 15 TOOTH LENGTH 3/8 ± 1/32 TYPE BD-50VDC MOTOR
Z 130
2.25 8:1
SECTION A-A
X 74.75 PINION
X 75.5 REF PT (FULLY EXTENDED TO 12" STROKE)
X 87.5 REF PT (FULLY RETRACTED -12" STROKE)
X ELEV PI

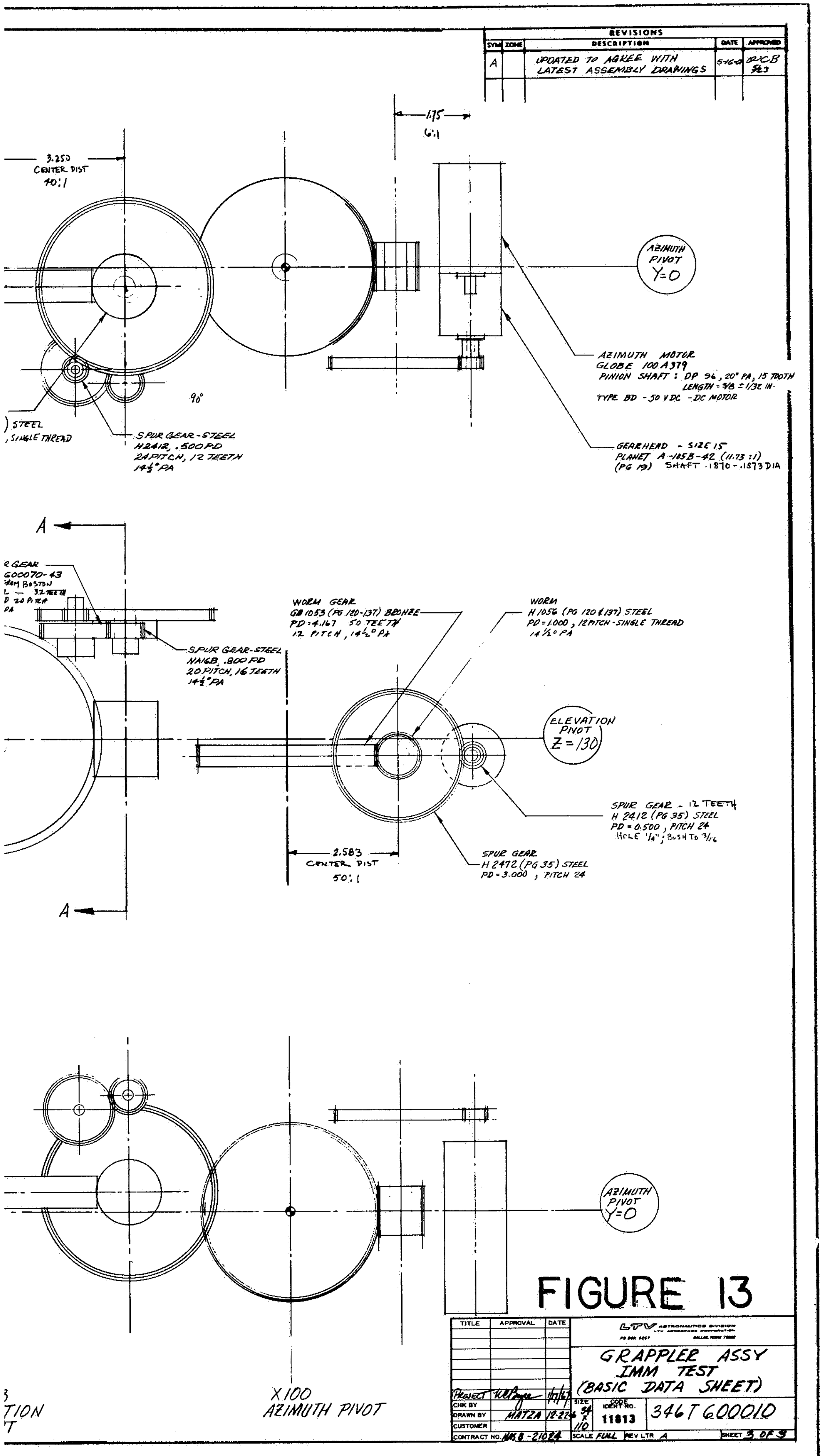
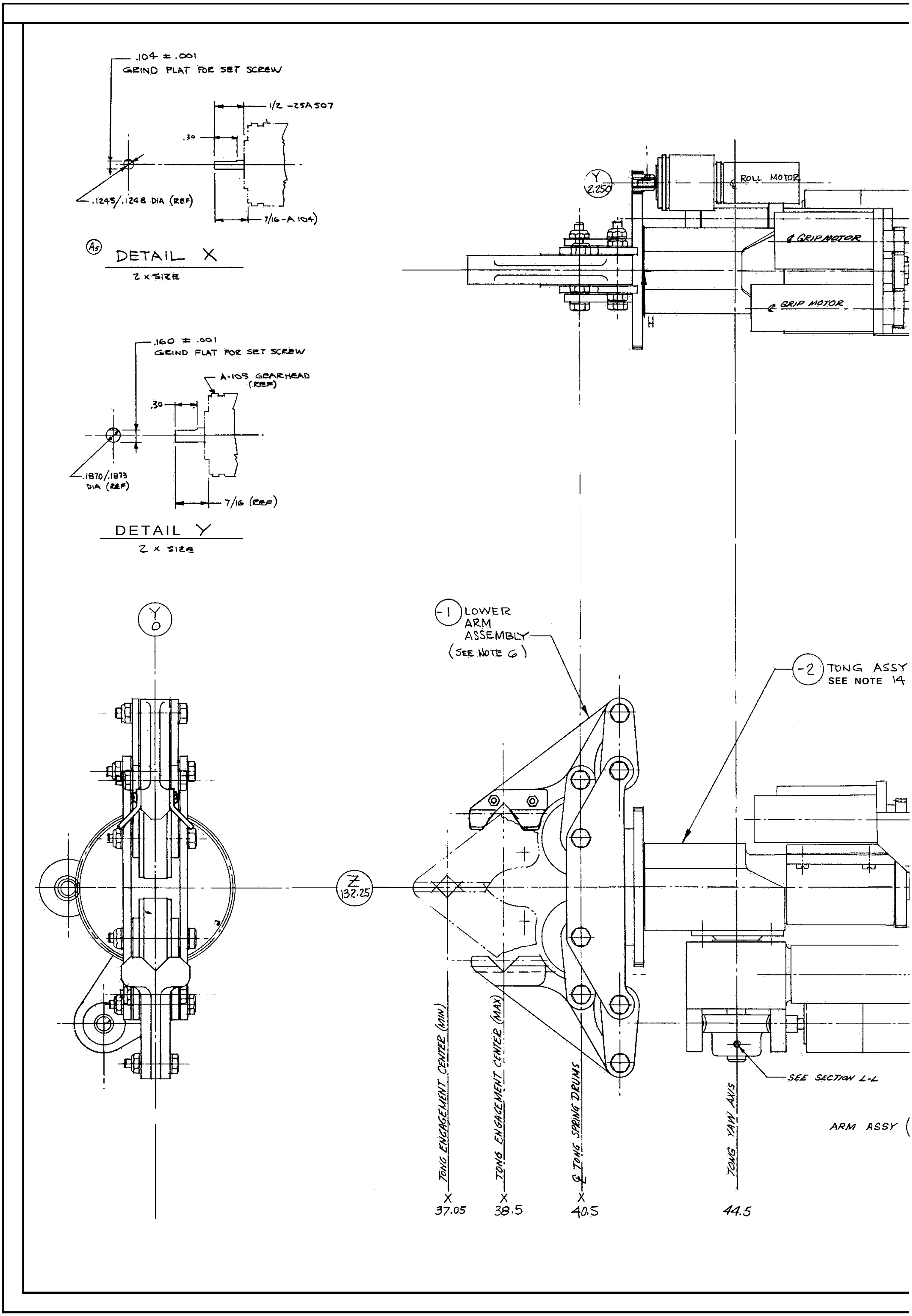
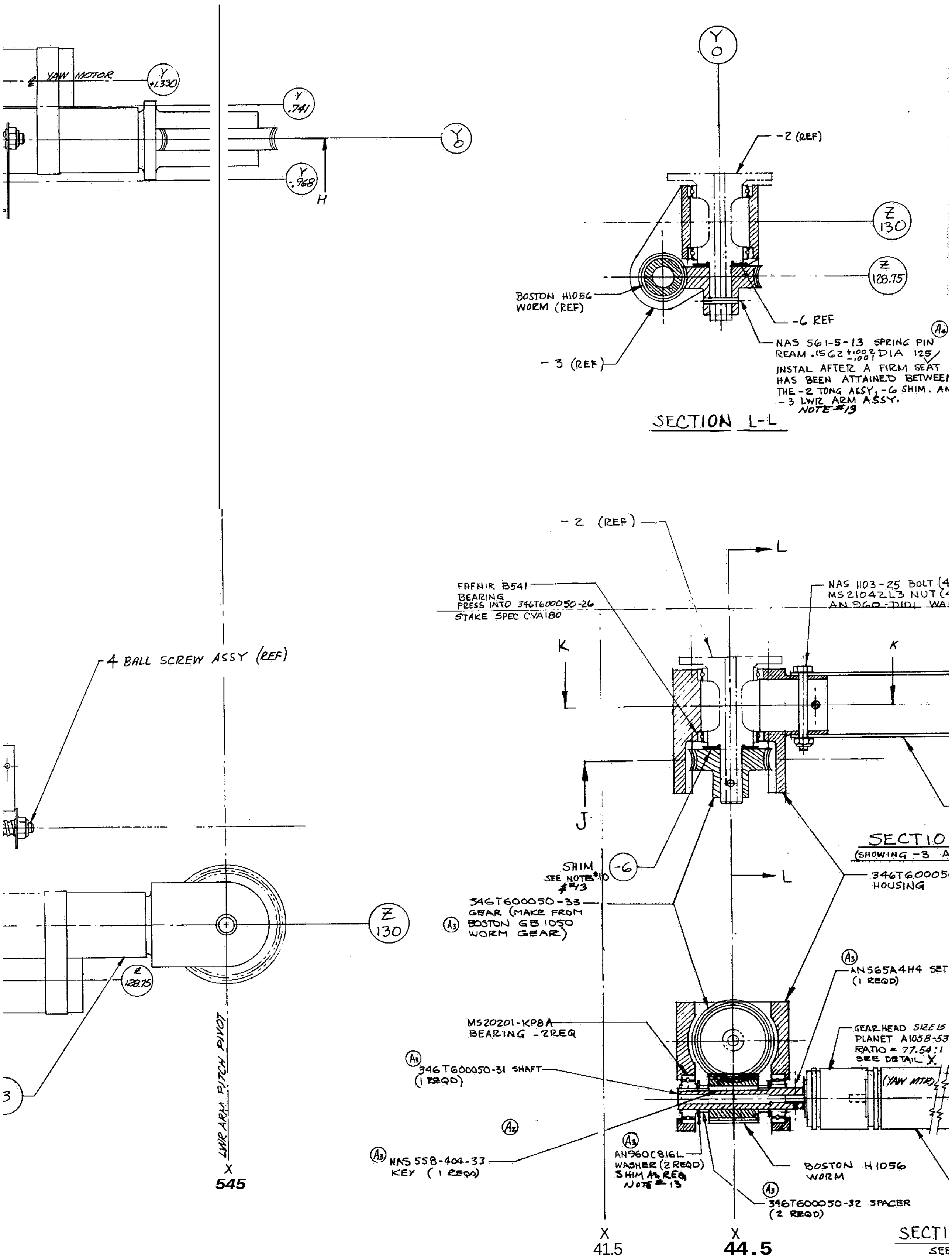
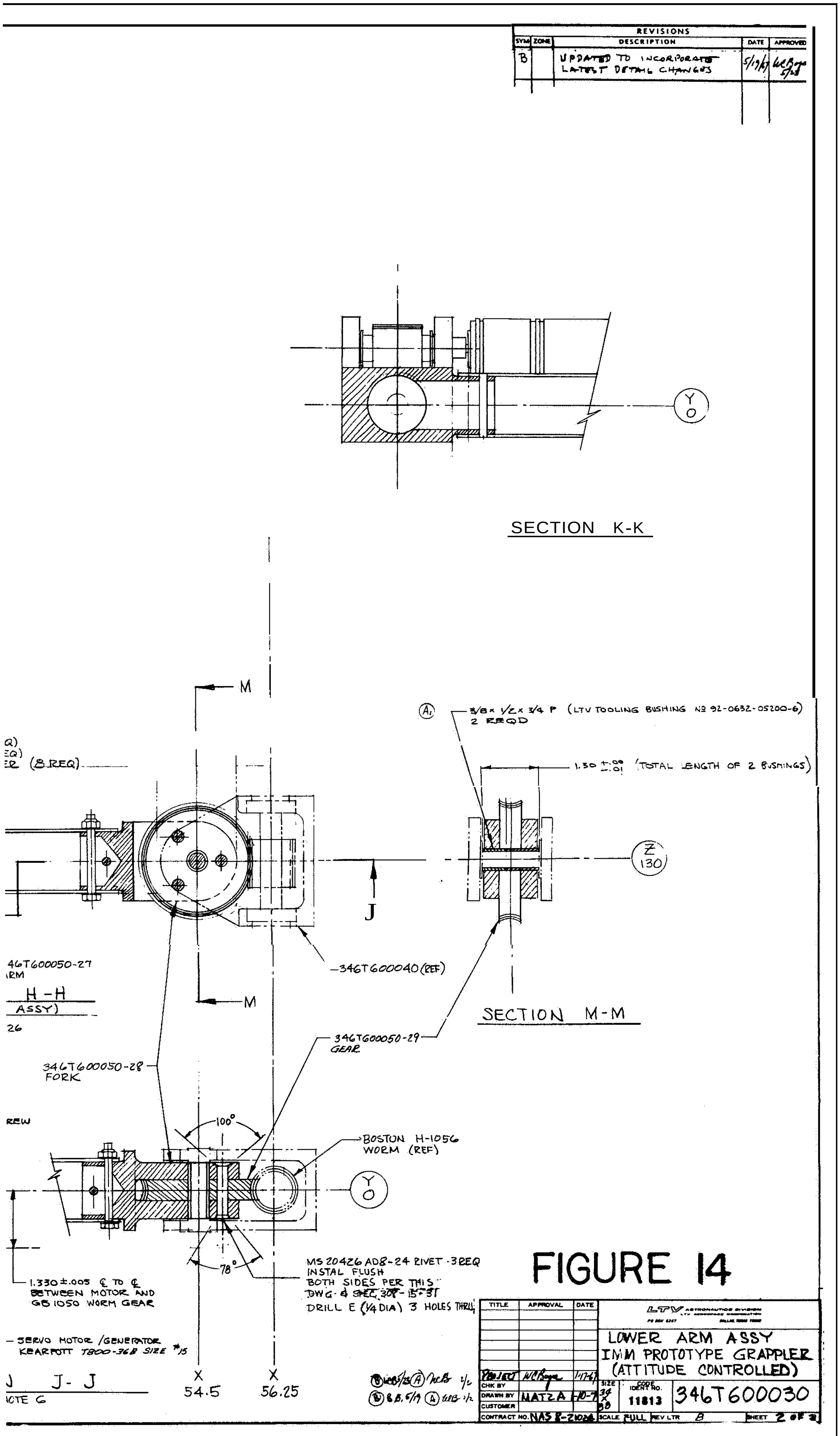

REVISIONS
SYM ZONE DESCRIPTION DATE APPROVED
A UPDATED TO AGREE WITH LATEST ASSEMBLY DRAWINGS
1.75
6:1
3.250
CENTER DIST
40:1
AZIMUTH PIVOT
Y=0
AZIMUTH MOTOR
GLOBE 100A379
PINION SHAFT : DP 96, 20° PA, 15 TOOTH
LENGTH = 3/8 ± 1/32 IN.
TYPE BD - 50 VDC - DC MOTOR
90°
) STEEL
, SINGLE THREAD
SPUR GEAR - STEEL
H2412, .500 PD
24 PITCH, 12 TEETH
14½° PA
GEARHEAD - SIZE 15
PLANET A-105B-42 (11.73 :1)
(PG 19) SHAFT .1870 - .1873 DIA
A
WORM GEAR
GB 1053 (PG 120-137) BRONZE
PD = 4.167 50 TEETH
12 PITCH, 14½° PA
WORM
H 1056 (PG 120 & 137) STEEL
PD = 1.000, 12 PITCH - SINGLE THREAD
14½° PA
SPUR GEAR - STEEL
NA16B, .800 PD
20 PITCH, 16 TEETH
14½° PA
ELEVATION PIVOT
Z = 130
SPUR GEAR - 12 TEETH
H 2412 (PG 35) STEEL
PD = 0.500, PITCH 24
HOLE ¼"; BUSH TO 3/16
2.583
CENTER DIST
50:1
SPUR GEAR
H 2472 (PG 35) STEEL
PD = 3.000, PITCH 24
A
AZIMUTH PIVOT
Y=0
TION
T
X100
AZIMUTH PIVOT
TITLE APPROVAL DATE
PROJECT
CHK BY
DRAWN BY MATZA 12-22
CUSTOMER
CONTRACT NO. NAS 8-21024
LTV ASTRONAUTICS DIVISION
LTV AEROSPACE CORPORATION
GRAPPLER ASSY
IMM TEST
(BASIC DATA SHEET)
SIZE
CODE IDENT NO. 11813
346T600010
SCALE FULL
REV LTR A
SHEET 3 OF 3

FIGURE 13


.104 ± .001
GRIND FLAT FOR SET SCREW
1/2 -25A507
.30
.1245/.1248 DIA (REF)
7/16-A 104)
DETAIL X
2 X SIZE
.160 ± .001
GRIND FLAT FOR SET SCREW
A-105 GEARHEAD (REF)
.30
.1870/.1873 DIA (REF)
7/16 (REF)
DETAIL Y
2 X SIZE
Y 2.250
ROLL MOTOR
℄ GRIP MOTOR
℄ GRIP MOTOR
H
Y 0
-1 LOWER ARM ASSEMBLY (SEE NOTE 6)
-2 TONG ASSY SEE NOTE 14
Z 132.25
SEE SECTION L-L
ARM ASSY (
TONG ENGAGEMENT CENTER (MIN)
TONG ENGAGEMENT CENTER (MAX)
℄ TONG SPRING DRUMS
TONG YAW AXIS
37.05
38.5
40.5
44.5

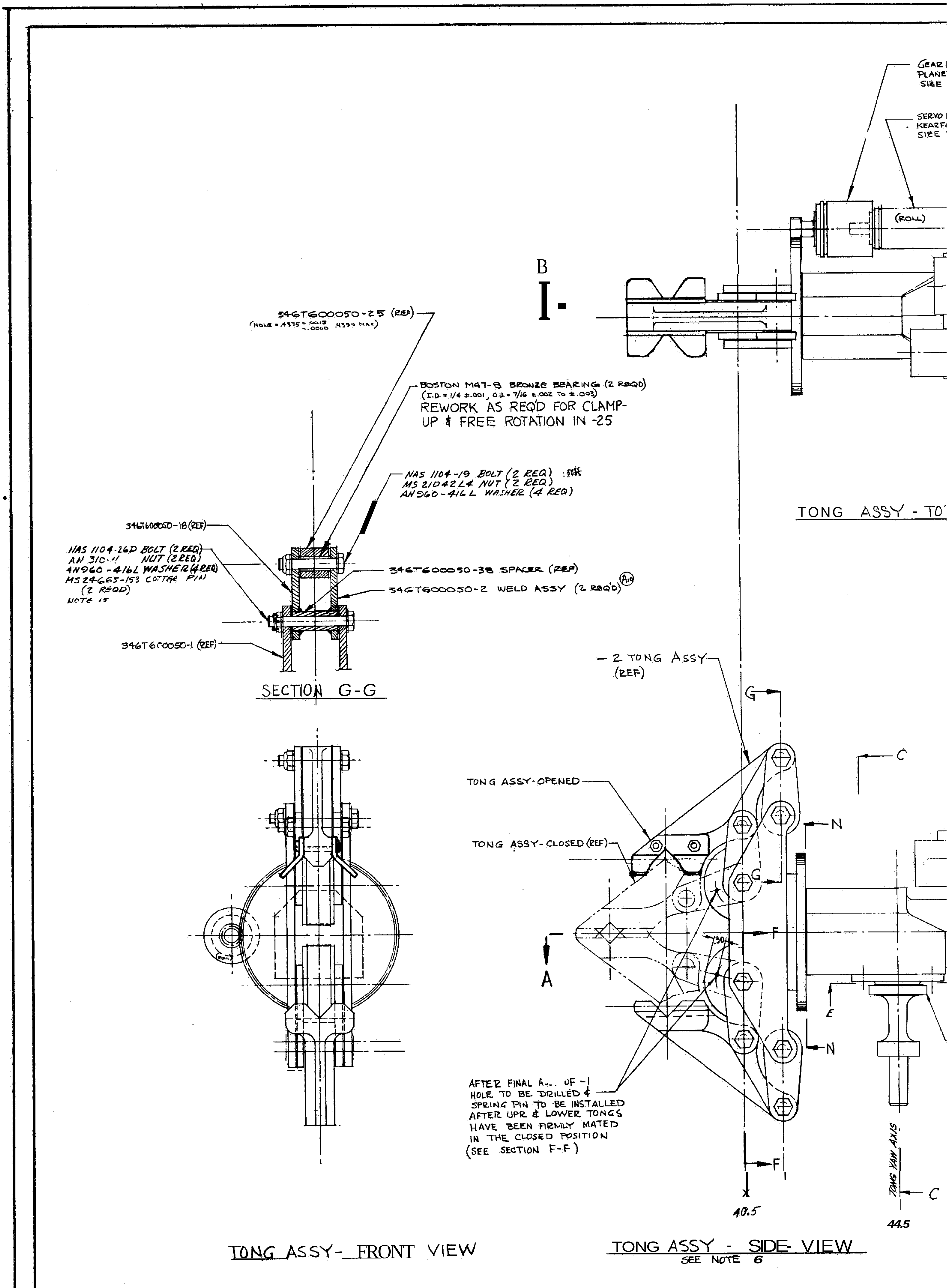


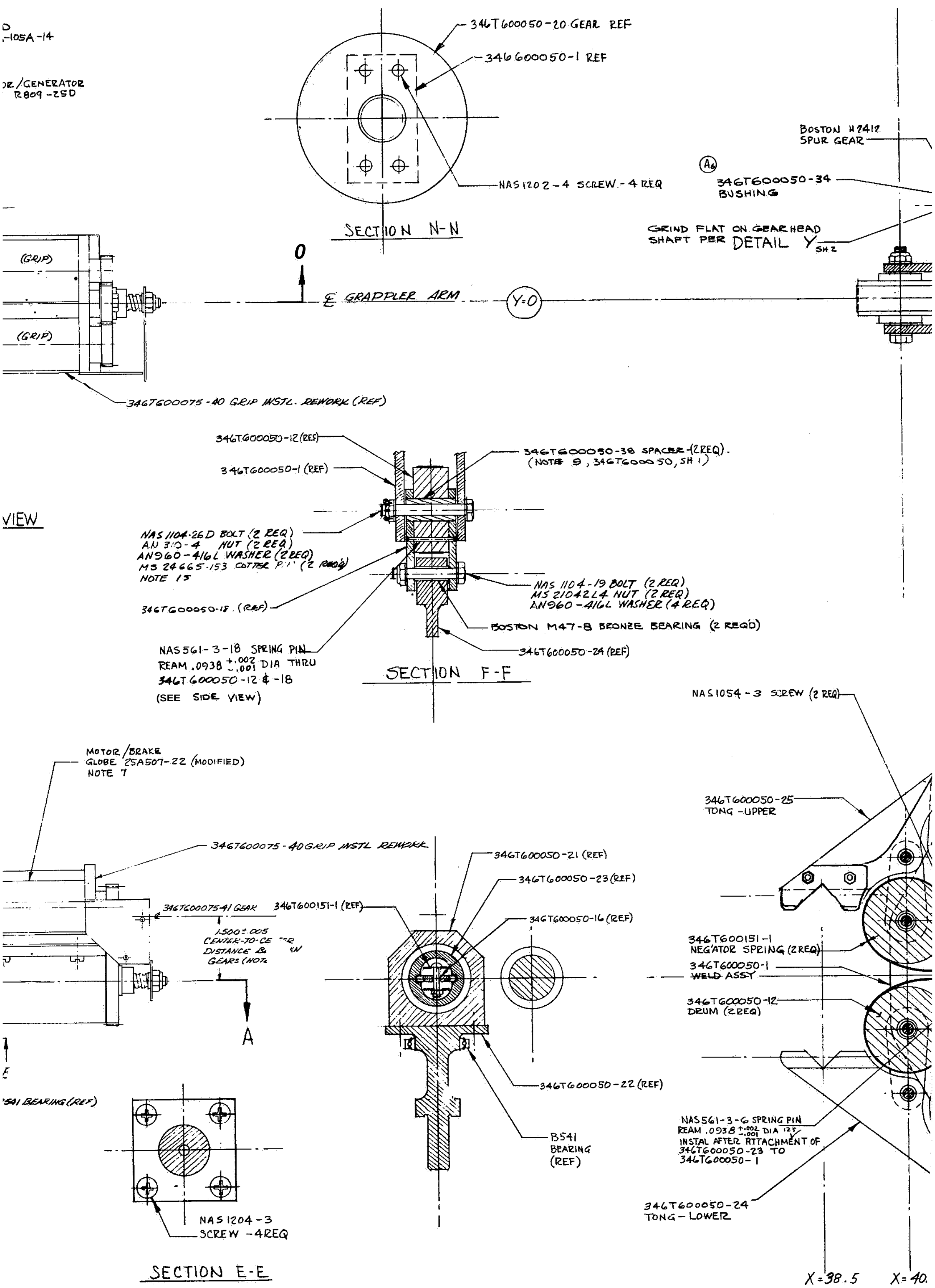
YAW MOTOR
Y +1.330
Y .741
Y 0
Y -.968
H
Y 0
-2 (REF)
Z 130
Z 128.75
BOSTON H1056 WORM (REF)
-6 REF
NAS 561-5-13 SPRING PIN
INSTAL AFTER A FIRM SEAT
HAS BEEN ATTAINED BETWEEN
THE -2 TONG ASSY, -6 SHIM, AN
-3 LWR ARM ASSY.
NOTE #13
- 3 (REF)
SECTION L-L
- 2 (REF)
L
FAFNIR B541 BEARING
PRESS INTO 346T600050-26
STAKE SPEC CVA180
NAS 1103-25 BOLT
MS21042L3 NUT
K
K
-4 BALL SCREW ASSY (REF)
J
SHIM
SEE NOTES #10 #13
-6
L
346T600050-33
GEAR (MAKE FROM BOSTON GB 1050 WORM GEAR)
HOUSING
Z 130
Z 128.75
AN565A4H4 SET
(1 REQD)
MS20201-KP8A
BEARING -2REQ
GEARHEAD SIZE 15
PLANET A105B-53
RATIO = 77.54:1
SEE DETAIL X
346T600050-31 SHAFT
(1 REQD)
(YAW MTR)
3
LWR ARM PITCH PIVOT
NAS 558-404-33
KEY (1 REQD)
AN960C816L
WASHER (2 REQD)
SHIM AS REQ
NOTE #13
BOSTON H1056
WORM
346T600050-32 SPACER
(2 REQD)
X 545
X 41.5
X 44.5



REVISIONS
SYM ZONE DESCRIPTION DATE APPROVED
B UPDATED TO INCORPORATE LATEST DETAIL CHANGES
Y O
SECTION K-K
M
A1 3/8 x 1/2 x 3/4 P (LTV TOOLING BUSHING NO 92-0632-05200-6) 2 REQD
1.30 (TOTAL LENGTH OF 2 BUSHINGS)
(8 REQ)
Z 130
J
346T600050-27
H-H
ASSY)
-346T600040 (REF)
M
SECTION M-M
346T600050-29 GEAR
346T600050-28 FORK
100°
BOSTON H-1056 WORM (REF)
Y O
78°
MS 20426 AD8-24 RIVET - 3 REQ
INSTAL FLUSH
BOTH SIDES PER THIS DWG
DRILL E (1/4 DIA) 3 HOLES THRU
1.330 ±.005 ℄ TO ℄ BETWEEN MOTOR AND GB 1050 WORM GEAR
SERVO MOTOR / GENERATOR KEARFOTT T800-36B SIZE #15
J J-J
X 54.5
X 56.25
TITLE APPROVAL DATE
LTV ASTRONAUTICS DIVISION
LOWER ARM ASSY
IMM PROTOTYPE GRAPPLER
(ATTITUDE CONTROLLED)
PROJECT W C Boyce
CHK BY
DRAWN BY MATZA
CUSTOMER
CONTRACT NO. NAS 8-21026
SIZE
CODE IDENT NO. 11813
346T600030
SCALE FULL
REV LTR B
SHEET 2 OF 2

FIGURE 14


(ROLL)
B
346T600050-25 (REF)
BOSTON M47-8 BRONZE BEARING (2 REQD)
REWORK AS REQ'D FOR CLAMP-UP & FREE ROTATION IN -25
NAS 1104-19 BOLT (2 REQ)
MS 21042L4 NUT (2 REQ)
AN960-416L WASHER (4 REQ)
TONG ASSY - TO
346T600050-18 (REF)
NAS 1104-26D BOLT (2 REQ)
AN 310-4 NUT (2 REQ)
AN960-416L WASHER (4 REQ)
MS24665-153 COTTER PIN (2 REQD)
NOTE 15
346T600050-38 SPACER (REF)
346T600050-2 WELD ASSY (2 REQ'D)
346T600050-1 (REF)
SECTION G-G
- 2 TONG ASSY (REF)
G
C
TONG ASSY-OPENED
TONG ASSY-CLOSED (REF)
N
F
A
E
AFTER FINAL A... OF -1 HOLE TO BE DRILLED & SPRING PIN TO BE INSTALLED AFTER UPR & LOWER TONGS HAVE BEEN FIRMLY MATED IN THE CLOSED POSITION (SEE SECTION F-F)
TONG YAW AXIS
40.5
44.5
TONG ASSY- FRONT VIEW
TONG ASSY - SIDE VIEW
SEE NOTE 6



-105A -14
/GENERATOR
R809 -25D
346T600050-20 GEAR REF
346600050-1 REF
NAS 1202-4 SCREW.-4 REQ
SECTION N-N
BOSTON H2412
SPUR GEAR
A6
346T600050-34
BUSHING
GRIND FLAT ON GEARHEAD
SHAFT PER DETAIL Y SH 2
0
(GRIP)
(GRIP)
℄ GRAPPLER ARM
Y=0
346T600075-40 GRIP INSTL. REWORK (REF)
346T600050-12 (REF)
346T600050-1 (REF)
346T600050-38 SPACER (2 REQ).
(NOTE 9, 346T600050, SH 1)
VIEW
NAS 1104-26D BOLT (2 REQ)
AN 310-4 NUT (2 REQ)
AN960-416L WASHER (2 REQ)
MS 24665-153 COTTER PIN (2 REQD)
NOTE 15
346T600050-18 (REF)
NAS 1104-19 BOLT (2 REQ)
MS 21042L4 NUT (2 REQ)
AN960-416L WASHER (4 REQ)
BOSTON M47-8 BRONZE BEARING (2 REQD)
346T600050-24 (REF)
NAS561-3-18 SPRING PIN
REAM .0938 +.002 -.001 DIA THRU
346T600050-12 & -18
(SEE SIDE VIEW)
SECTION F-F
NAS1054-3 SCREW (2 REQ)
MOTOR/BRAKE
GLOBE 25A507-22 (MODIFIED)
NOTE 7
346T600050-25
TONG -UPPER
346T600075-40 GRIP INSTL REWORK
346T600050-21 (REF)
346T600050-23 (REF)
346T600075-41 GEAR
346T600151-1 (REF)
346T600050-16 (REF)
1.500±.005
CENTER-TO-CE
DISTANCE B
GEARS (NOTE
A
346T600151-1
NEG'ATOR SPRING (2 REQ)
346T600050-1
WELD ASSY
346T600050-12
DRUM (2 REQ)
541 BEARING (REF)
346T600050-22 (REF)
B541
BEARING
(REF)
NAS561-3-6 SPRING PIN
REAM .0938 +.002 -.001 DIA
INSTAL AFTER ATTACHMENT OF
346T600050-23 TO
346T600050-1
346T600050-24
TONG - LOWER
NAS 1204-3
SCREW -4 REQ
SECTION E-E
X=38.5
X=40.

SECTION C-C

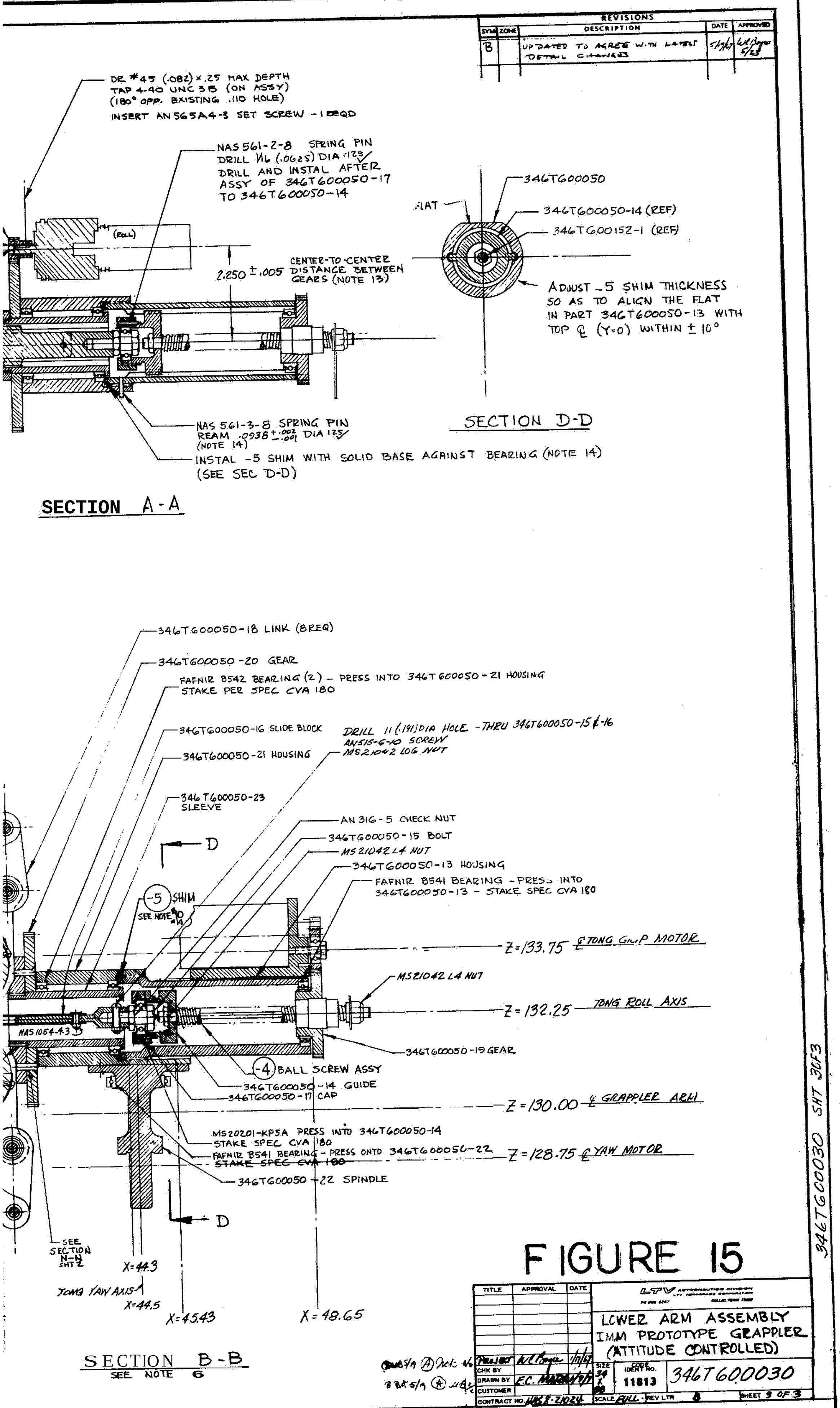

REVISIONS
SYM ZONE DESCRIPTION DATE APPROVED
B UPDATED TO AGREE WITH LATEST DETAIL CHANGES
DR #45 (.082) x .25 MAX DEPTH TAP 4-40 UNC 3B (ON ASSY) (180° OPP. EXISTING .110 HOLE)
INSERT AN565A4-3 SET SCREW - 1 REQD
NAS 561-2-8 SPRING PIN DRILL 1/16 (.0625) DIA 125 DRILL AND INSTAL AFTER ASSY OF 346T600050-17 TO 346T600050-14
(ROLL)
2.250 ± .005 CENTER-TO-CENTER DISTANCE BETWEEN GEARS (NOTE 13)
NAS 561-3-8 SPRING PIN REAM .0938 +.002 -.001 DIA 125 (NOTE 14)
INSTAL -5 SHIM WITH SOLID BASE AGAINST BEARING (NOTE 14) (SEE SEC D-D)
SECTION A-A
346T600050
FLAT
346T600050-14 (REF)
346T600152-1 (REF)
ADJUST -5 SHIM THICKNESS SO AS TO ALIGN THE FLAT IN PART 346T600050-13 WITH TOP ℄ (Y=0) WITHIN ± 10°
SECTION D-D
346T600050-18 LINK (8 REQ)
346T600050-20 GEAR
FAFNIR B542 BEARING (2) - PRESS INTO 346T600050-21 HOUSING STAKE PER SPEC CVA 180
346T600050-16 SLIDE BLOCK
DRILL 11 (.191) DIA HOLE - THRU 346T600050-15 & -16
AN515-6-10 SCREW
MS21042 L06 NUT
346T600050-21 HOUSING
346T600050-23 SLEEVE
AN 316-5 CHECK NUT
346T600050-15 BOLT
MS21042 L4 NUT
346T600050-13 HOUSING
FAFNIR B541 BEARING - PRESS INTO 346T600050-13 - STAKE SPEC CVA 180
D
-5 SHIM
SEE NOTE 10 14
Z = 133.75 ℄ TONG GRIP MOTOR
MS21042 L4 NUT
Z = 132.25 TONG ROLL AXIS
NAS 1054-4-3
346T600050-19 GEAR
-4 BALL SCREW ASSY
346T600050-14 GUIDE
346T600050-17 CAP
Z = 130.00 ℄ GRAPPLER ARM
MS20201-KP5A PRESS INTO 346T600050-14 STAKE SPEC CVA 180
FAFNIR B541 BEARING - PRESS ONTO 346T600050-22 STAKE SPEC CVA 180
Z = 128.75 ℄ YAW MOTOR
346T600050-22 SPINDLE
D
SEE SECTION N-N SHT 2
X = 44.3
TONG YAW AXIS
X = 44.5
X = 45.43
X = 48.65
SECTION B-B
SEE NOTE 6
346T600030 SHT 3 OF 3
TITLE APPROVAL DATE
LTV ASTRONAUTICS DIVISION
LOWER ARM ASSEMBLY IMM PROTOTYPE GRAPPLER (ATTITUDE CONTROLLED)
PROJECT
CHK BY
DRAWN BY F.C. MADDY
CUSTOMER
CONTRACT NO. NAS 8-21024
SIZE
CODE IDENT NO. 11813
346T600030
SCALE FULL
REV LTR B
SHEET 3 OF 3

FIGURE 15

6.1.3). Also shown is the tubular section used during some of the anchoring tests. During preliminary evaluation of the tongs it was discovered that while the original design was effective after engagement, that due to its narrow width it allowed little margin for error during the anchoring maneuver. Consequently, sheet metal angles were added to extend the width of the jaw, thus providing greater gripping area.

5.2.3 POSITION CONTROLLER

The two controllers are similar in appearance and construction, and although they differ in a number of important characteristics, there are also several components which are common to both. This section discusses the simpler of the two, the position controller. Figure 16a shows a comparison of the two controllers and Figure 16b is a view looking down on the control station, showing the position controller at left, the attitude controller at right, and the manipulator in the background.

The position controller produces simple on-off switch commands for controlling the gross position of the grappler arm. It is comprised of four major elements, the outer support, an intermediate housing, an inner housing and a control pistol grip. Figure 17 is the assembly drawing for the position controller.

The elements of the controller are pivoted similar to the gimbals of a gyroscope in order to achieve the proper sense orientation of the controls, so as to insure that movement of the control grip duplicates the same sense of motion as the control output and hence of the grappler (or vehicle). Vertical motion of the stick grip actuates on-off switches which command vertical translation (or elevation) of the vehicle (or grappler). [Inasmuch as it is beyond the scope of this test program to simulate anything other than 3 Degrees of Vehicle Freedom (Fore/Aft, Right/Left and Yaw Right/Yaw Left), switching commands for Vertical Translation and for Pitch and Roll affect only the manipulator in the test system]. Lateral motion of the grip provides switch commands for lateral translation of the vehicle or of the manipulator arm (azimuth). Fore and aft grip motion commands extension of the grappler or fore/aft vehicle translation. Each of the control motions is obtained by means of similar internal linkages. This is true also of the motions of the right hand controller. Similarly the switch actuation and centering of controls is almost identical about all axes of both controllers. Figure 18 shows how switch actuation and centering action are obtained by means of spring-loaded centering scissors. Figures 19 and 20 show the similarity of the details of the two controllers.

Up-down control motion of the left hand control grip is achieved by means of a four-bar linkage, one element of which is the grip itself, and another element of which is the spring-loaded centering scissors. This linkage is supported within the inner housing, which in turn is pivoted on an

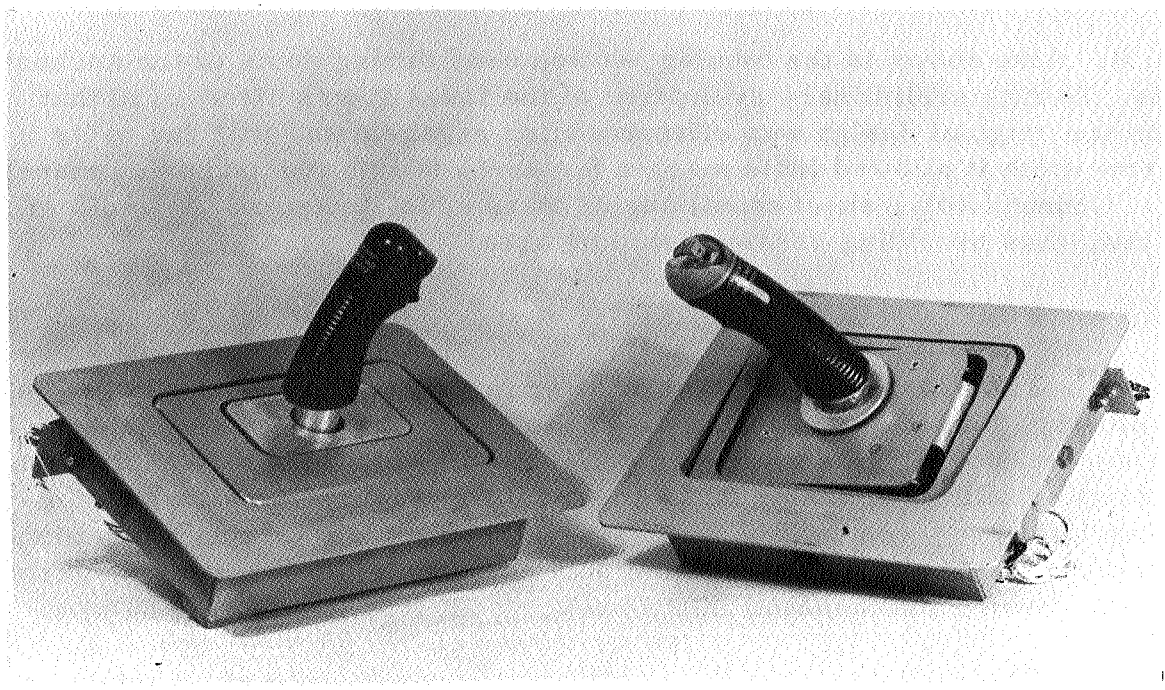
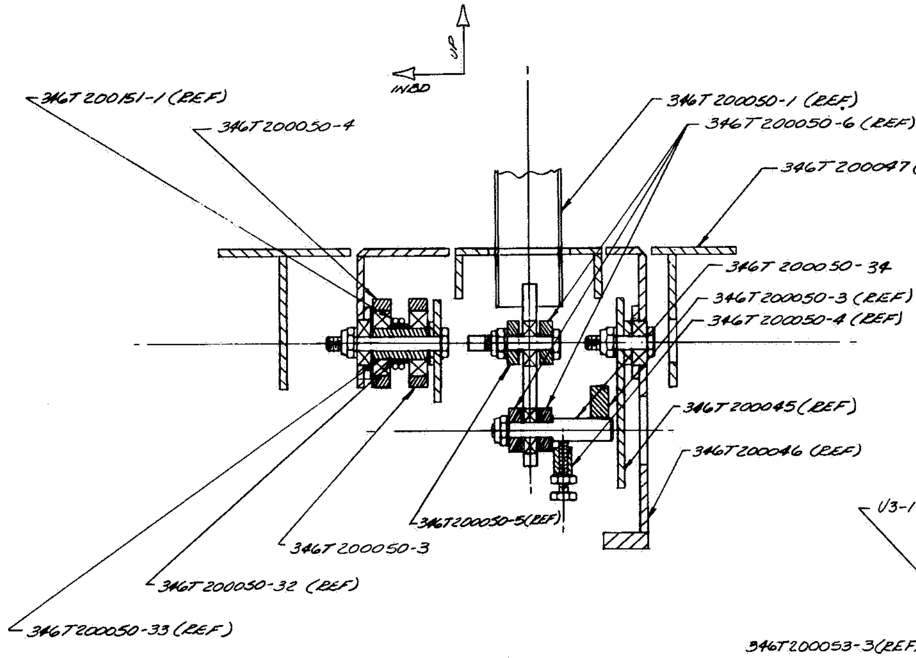
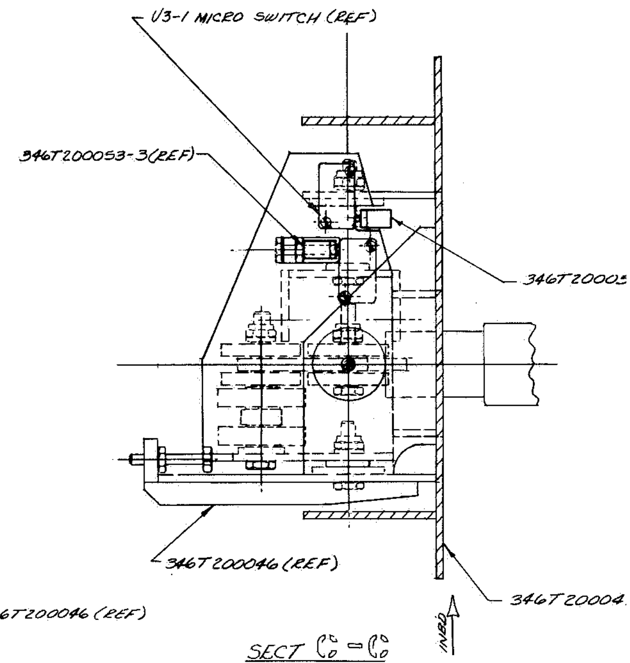


Figure 16a - Comparison of Flight Controllers; Position Controller, 346T200040 at Left and Attitude Controller, 346T200030 at Right

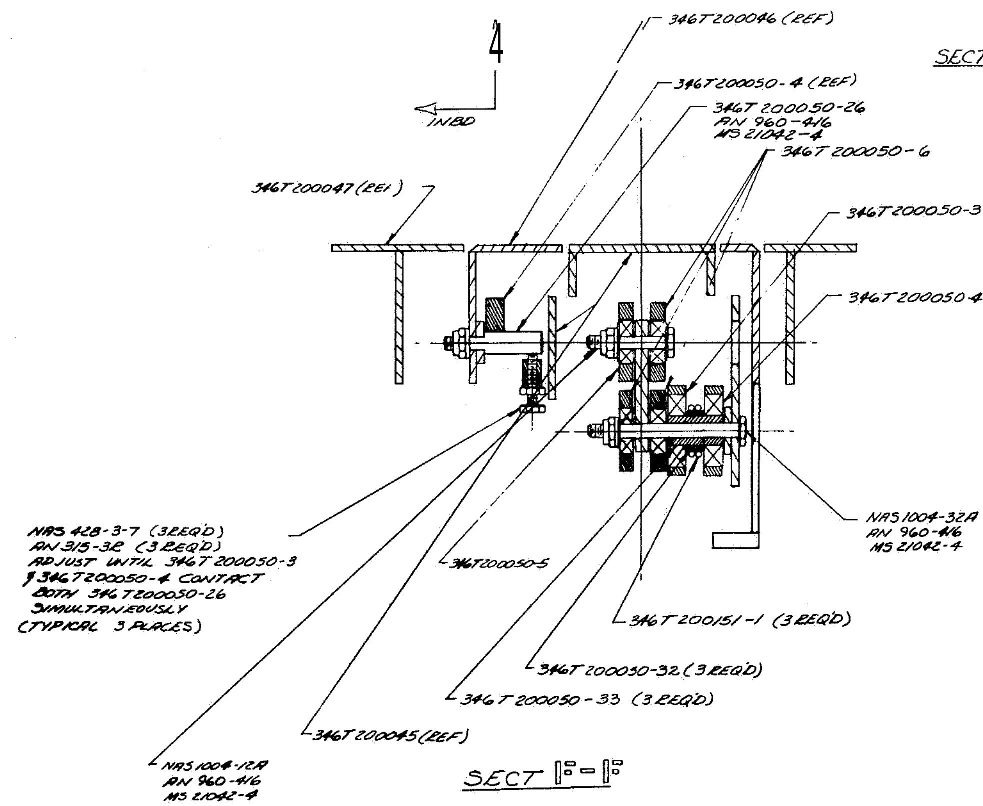
Figure 16b - Top View of Manipulator Control Station with Position Controller at Left, Attitude Controller at Right and Manipulator in Background. Control Switch (Center Left) is manipulator Power Shutoff, While Switch in in Center Foreground is Experimental Gain Selector Switch



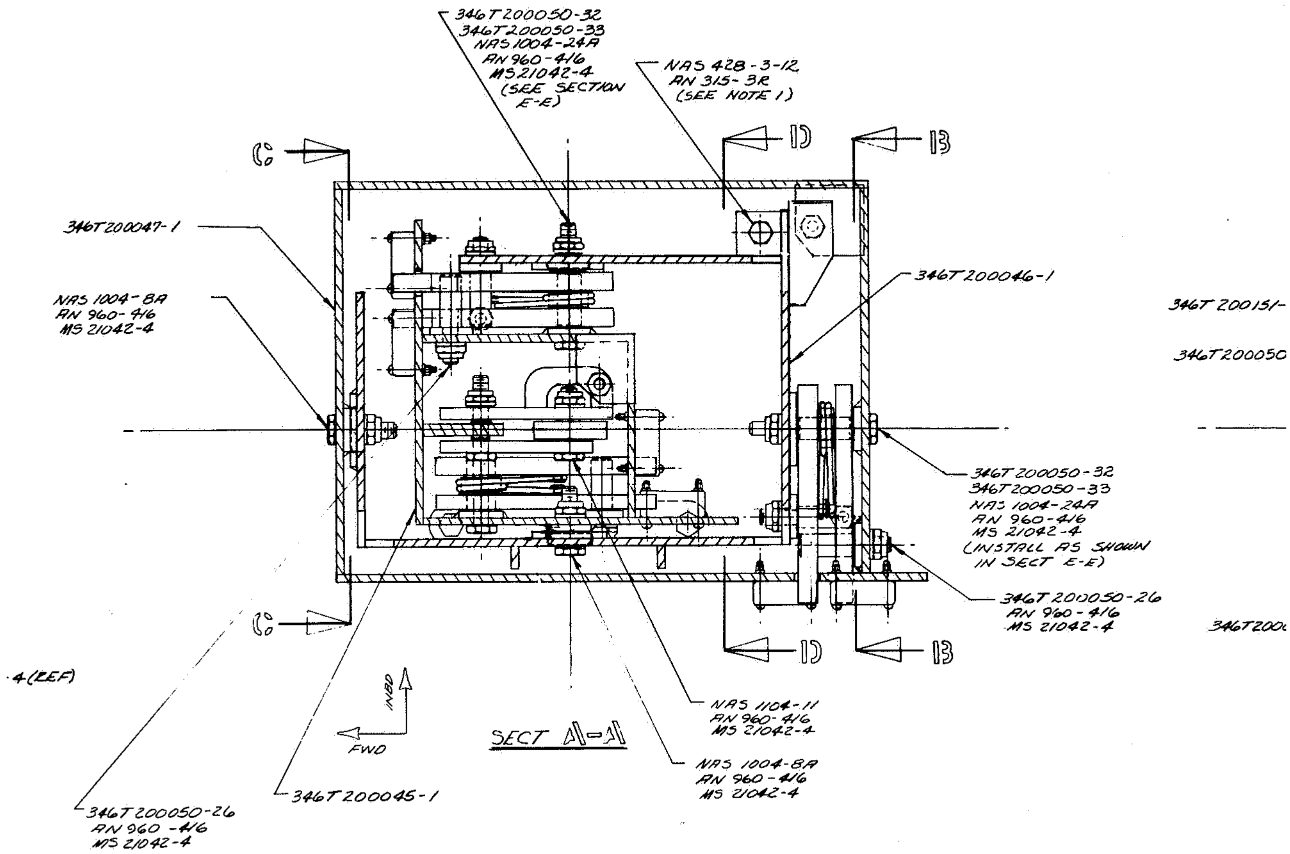
SECT E-E



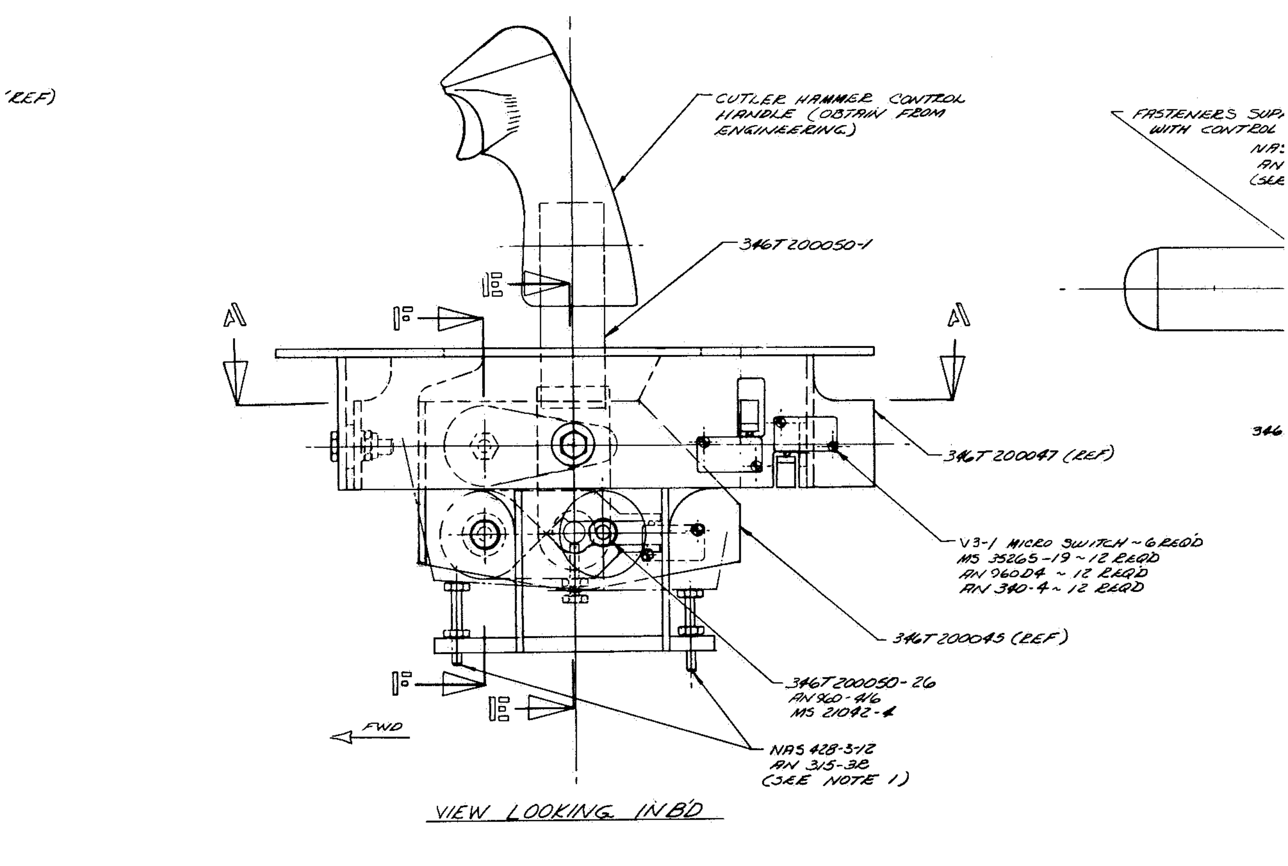
SECT C-C



SECT F-F



SECT A-A



VIEW LOOKING INBD

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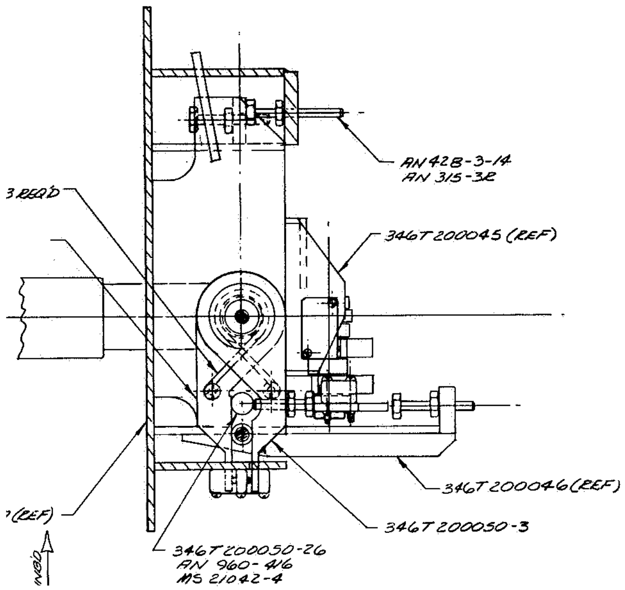
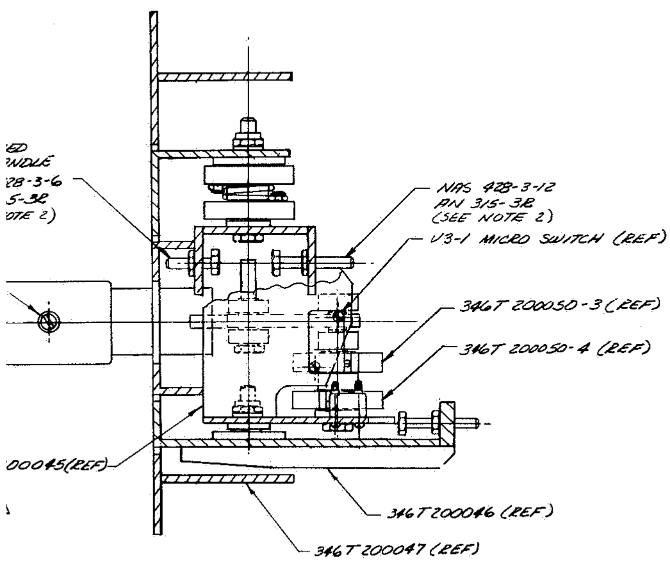


SECT B-B



SECT D-D

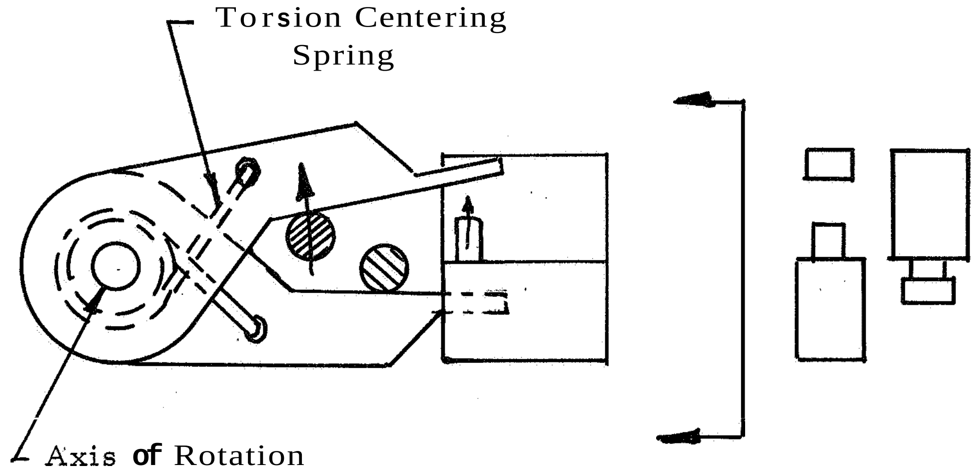
CONTROLLER ASSY
IMM PROTOTYPE GRAPPLER
POSITION

FIGURE 17

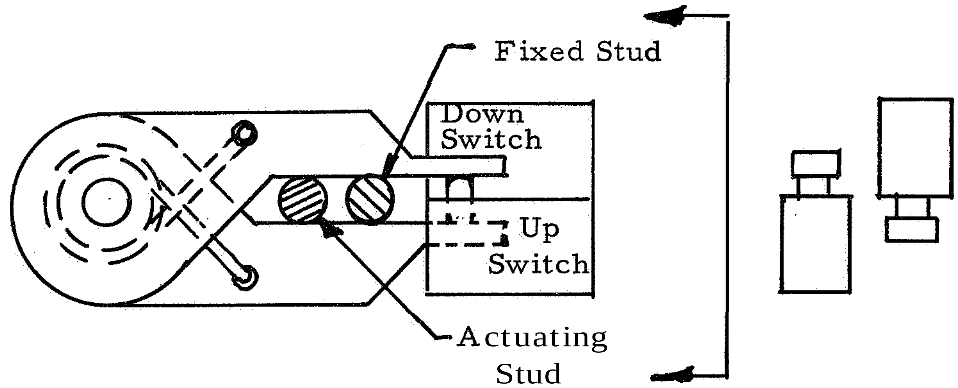
DN BY	PROJECT
P. COLLEONI 2/6/67	W. C. BOYCE 2/6/7

LTV ASTRONAUTICS DIVISION, LTV AEROSPACE CORPORATION, P.O. BOX 6267, DALLAS, TEXAS 75222

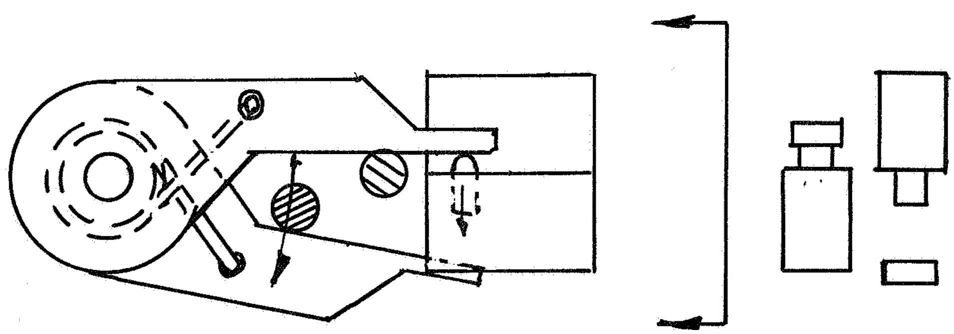
SIZE	CODE IDENT NO.	
34 50	11813	346T200040
SCALE 1/1	REV LTR	SHEET 2



(a) Plunger of normally closed "up" switch released by upward motion of actuating stud.



(b) Both switches off when both links are centered against both studs.



(c) Plunger of normally closed "down" switch released by downward motion of actuating stud.

FIGURE 18 SWITCH ACTUATION BY CENTERING SCISSORS

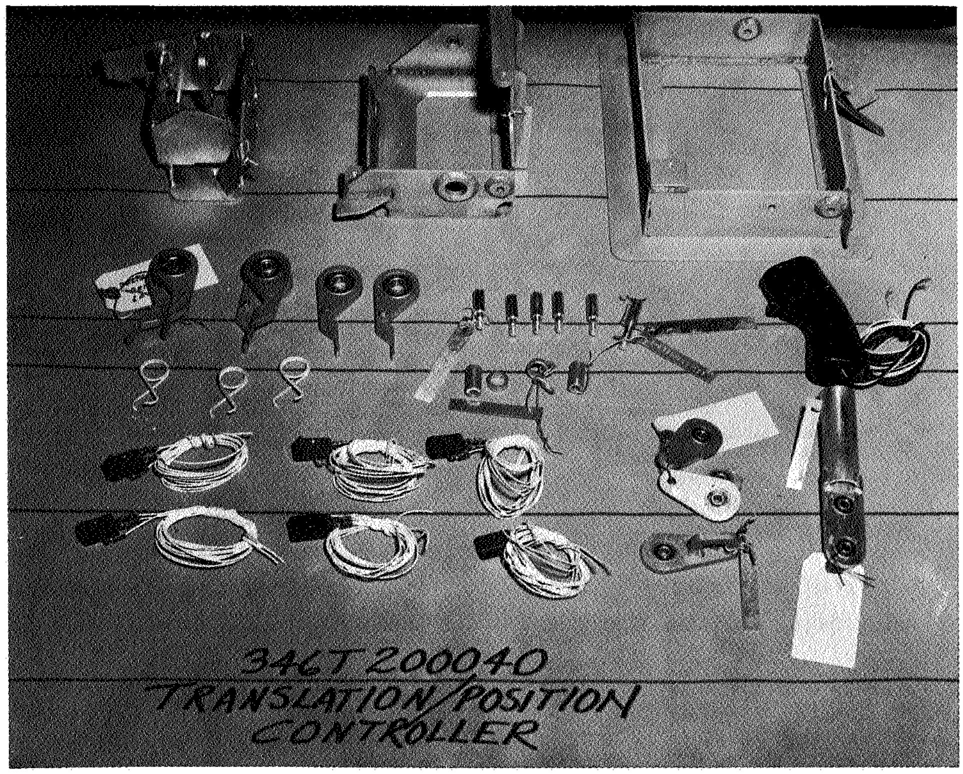


Figure 19 - Details and Subassemblies of Position Controller. At left, center are Centering Scissors

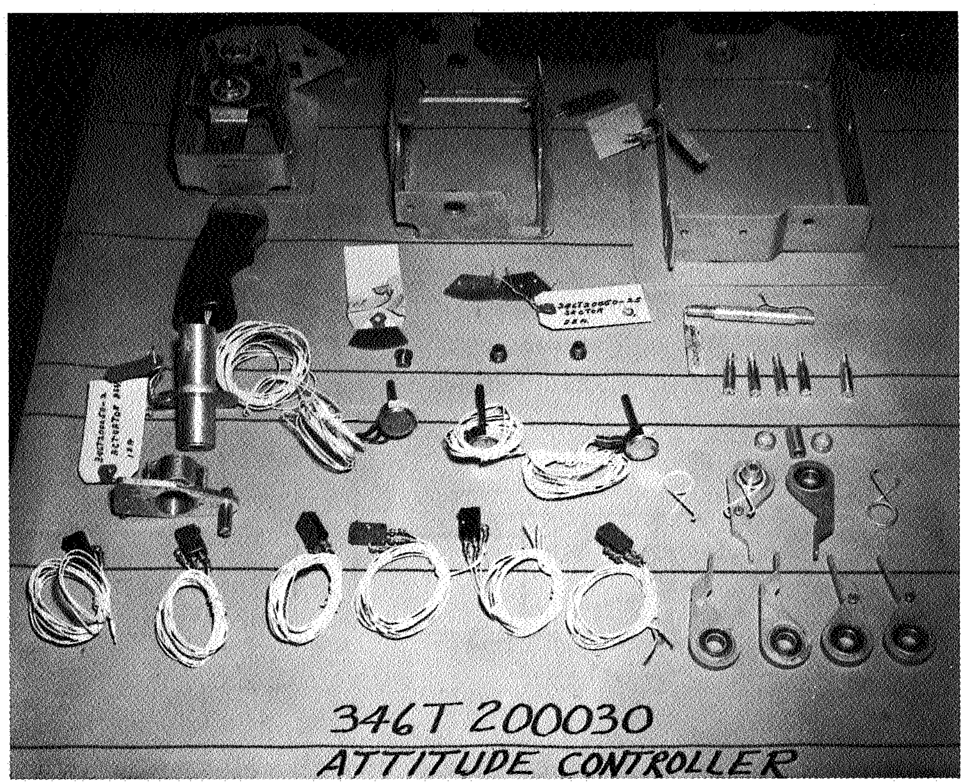


Figure 20 - Details and Subassemblies of Attitude Controller. Centering Scissors in Right Foreground, Rate Control Potentiometers and Gear Sectors, Center

intermediate housing to permit fore and aft control motion. This pivoting of the inner housing causes distortion of the fore-aft centering scissors and, at the same time, operates the appropriate switch.

Lateral movement of the control grip causes the intermediate housing to rock laterally in the outer support housing, distorting lateral centering scissors and actuating appropriate lateral control switches, in a similar manner. Figure 21 shows the underside of the position controller, revealing details of the four-bar linkage and showing the three identical centering scissors.

The trigger switch contained in the left hand pistol grip commands the control selection for either the vehicle or for the manipulator. When this trigger is released, both controllers command the vehicle propulsion system. Actuation of the trigger causes both controllers to be switched over to command of the manipulator.

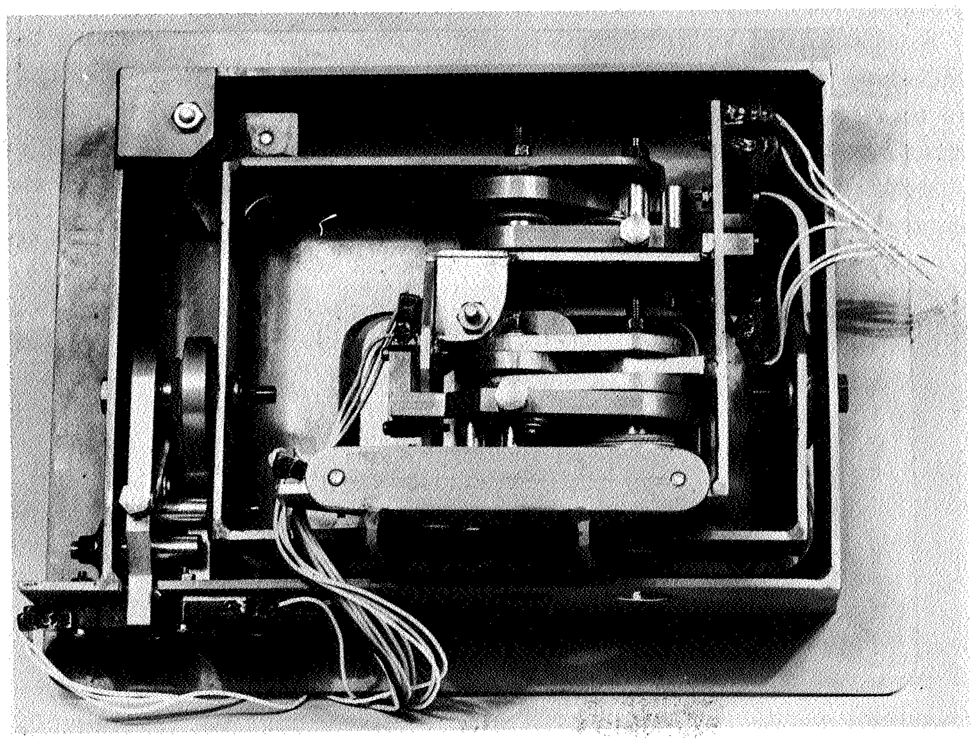


Figure 21 - Bottom View of Position Controller, Note Three Pairs of similar centering Scissors for actuation of on-off control switches

5.2.4 ATTITUDE CONTROLLER

The right hand controller commands changes in orientation or attitude of either the manipulator lower arm or of the vehicle, depending upon actuation of the selector trigger on the left hand controller. The right hand controller also commands opening and closing of the manipulator tongs, by means of a switch on top of the pistol grip. This spring-loaded center-off switch causes the tongs to close when moved forward, and to open when moved aft.

The attitude controller is similar in construction and function to the left hand controller, with two notable exceptions. In addition to actuation of on-off switches, continued angular motions of the control grip produces modulated control signals which vary the rate of the lower arm drive motors as a function of control displacement. Secondly, the right hand pistol grip rotates about its long axis for yaw control, rather than moving vertically like the left hand controller. All switch actuation and centering is achieved in the same manner as in the left hand controller. Figure 23 is the assembly drawing for the attitude controller.

Rotation of the control grip takes place about a vertical spindle mounted on the inner housing. After actuation of the appropriate on-off yaw control switch, continued rotation causes a gear sector to rotate a potentiometer. Roll control is achieved in the same manner by rolling the intermediate housing laterally within the outer support structure. Figure 22 shows the underside of the attitude controller. Clearly visible are the three control potentiometers, and the centering scissors for roll and pitch. The yaw centering scissors are hidden by the central cruciform structure which supports the yaw pivot spindle.

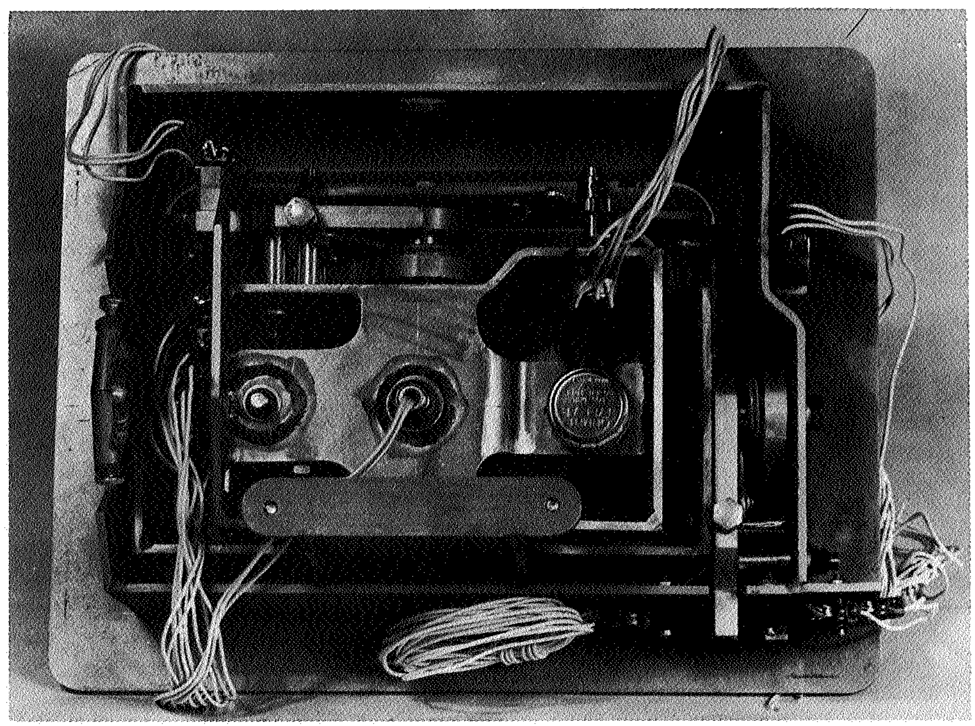
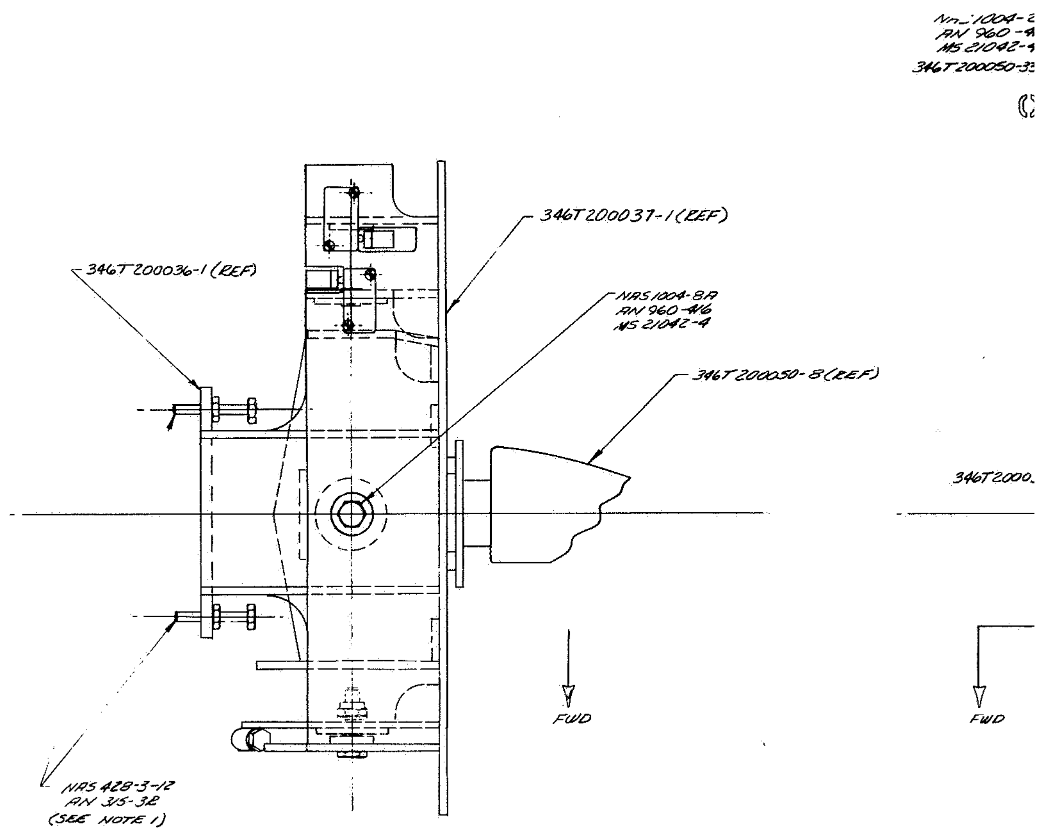
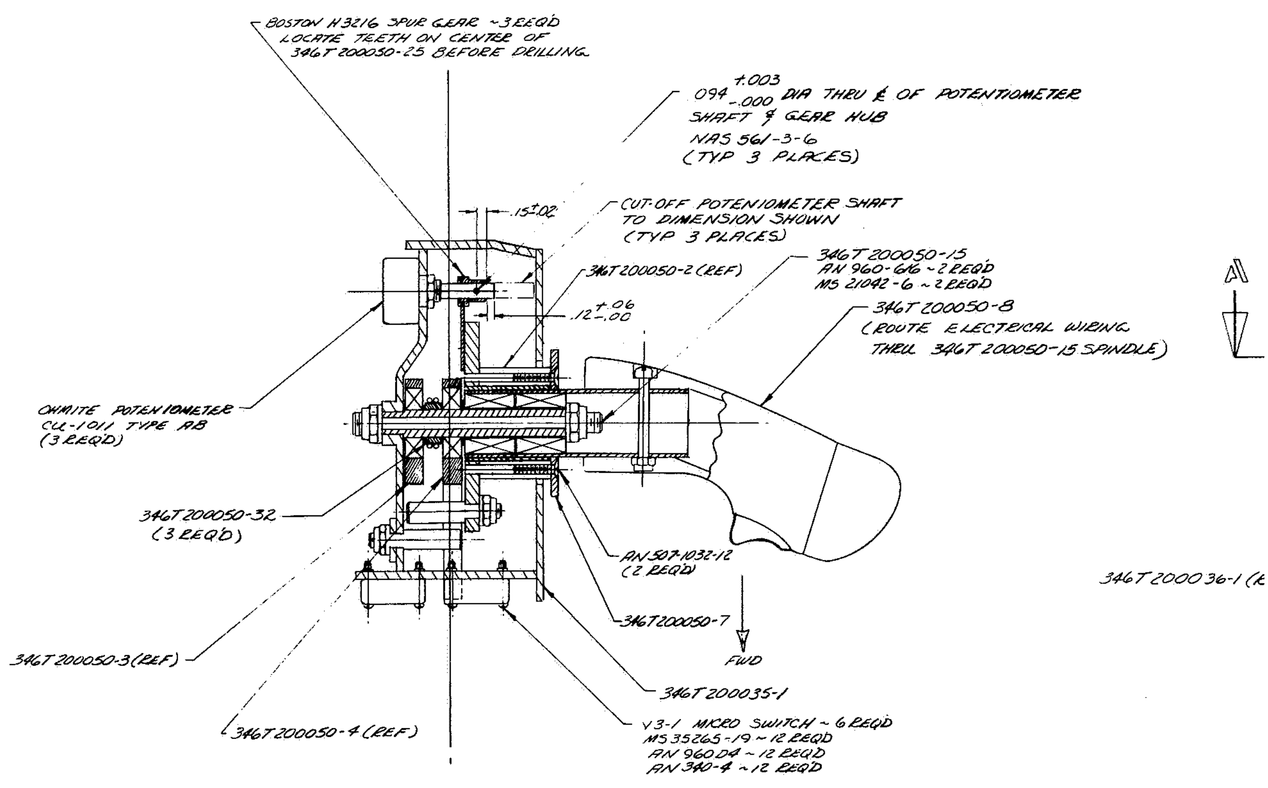


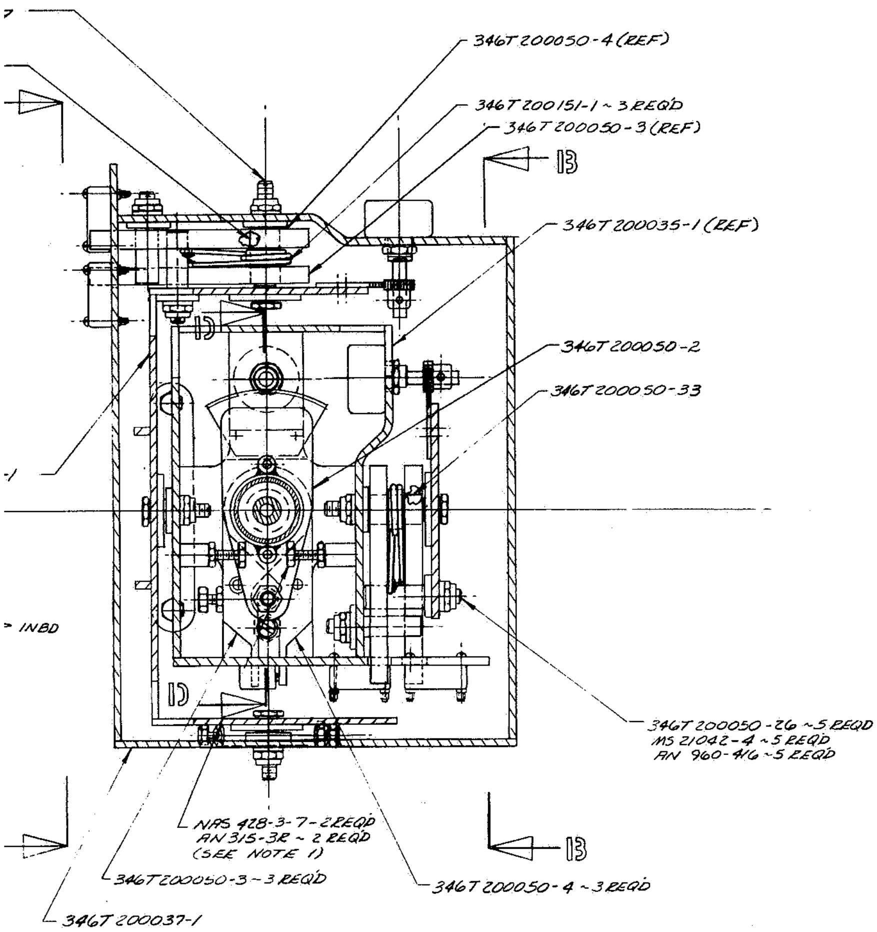
Figure 22 - Bottom View of Attitude Controller. Note Rate Control Potentiometers and Spring-Loaded Centering Scissors for Switch Actuation



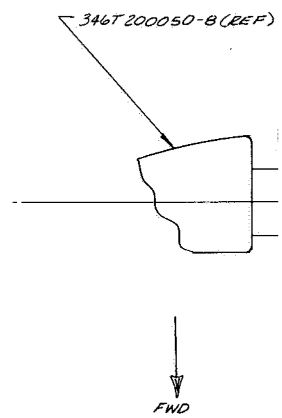
SECT C-C

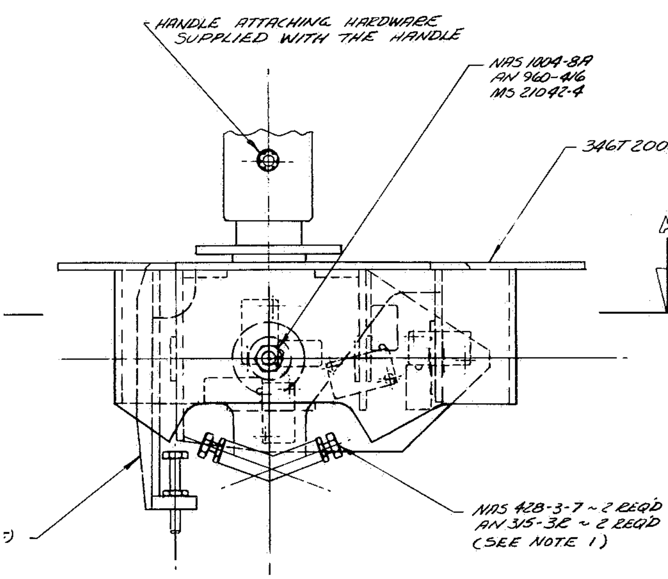


SECT D-D



SECT A-A





ASSY
VIEW LOOKING AFT

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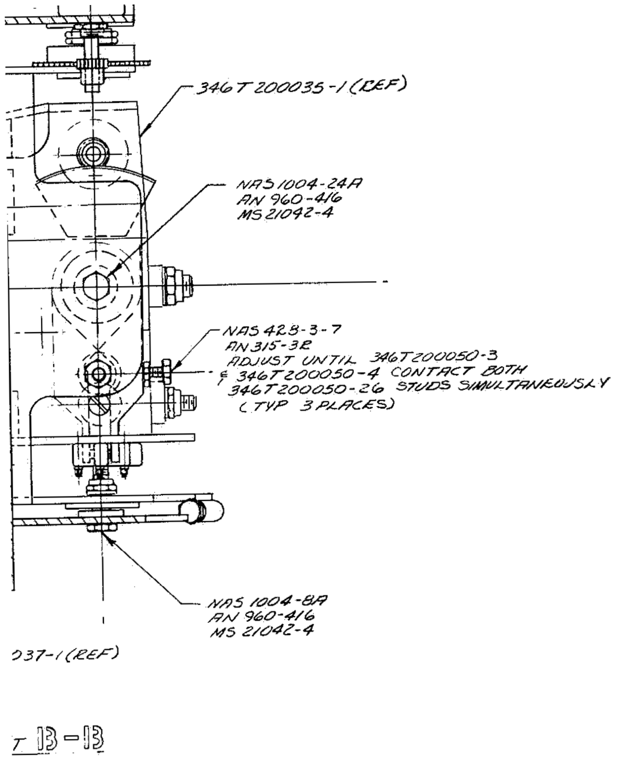


CONTROLLER ASSY
IMM PROTOTYPE GRAPPLER
ATTITUDE

FIGURE **23**

LTV ASTRONAUTICS DIVISION
LTV AEROSPACE CORPORATION
P.O. BOX 6267 DALLAS, TEXAS 75222

SIZE | CODE IDENT NO. 11813 | 346T200030
SCALE FULL | REV LTR | SHEET 2

R. Colleson 7/6/67
DRN. BY | PROJECT

5.3 ELECTRICAL SYSTEM

5.3.1 SUMMARY OF OVERALL SYSTEM OPERATION

The actuators for the Prototype Manipulator are briefly described in this section. They are discussed below under three functional headings; tongs drive, attitude drives, and position drives, since the drives associated with each are similar in function and mechanization. Table III lists the characteristics of each drive function,

Figure 24 presents a functional block diagram of the IMM Manipulator Electrical System, which is shown in greater detail in the System Schematic, Figure 26. Figure 25 shows a portion of the electrical installation in the Controller Pedestal.

5.3.2 TONGS DRIVE

The tongs drive consists of a pair of motors operating in tandem, a brake, and associated external gearing. The motors are permanent magnet, 24 volt direct current motors. The direction of rotation is controlled by connecting the supply voltage to one or the other of the motor armature terminals and grounding the other. Power is supplied to the grip motors through power relays. In the de-energized condition both drive motor armature terminals are grounded to provide some dynamic braking and simplify switching logic. When the grip command switch is actuated, the appropriate power relay is energized and supply voltage is applied to the proper motor(s) terminal. A brake on the smaller motor holds the tongs in any chosen position when the motors are not energized. Application of power to the motors disengages the solenoid actuated brake.

A limit switch is provided to prevent overrunning during grip opening since the use of a mechanical stop is unfeasible. At maximum grip opening, the limit switch opens the ground lead on the "open" power relay coil, de-energizes the relay, removes power from the grip motors, engages the brake, and disables the "open" function on the grip. Since the "close" function is not affected by de-energizing the "open" relay, the grip can be closed by actuating the grip command switch to the "close" position. No electrical limit is provided (nor is feasible) in the closed position since the grip provides an adequate mechanical stop, and since the closed position of the tongs is a variable.

5.3.3 ATTITUDE DRIVES

The pitch, roll, and yaw drives are functionally equivalent, rate proportional servos and differ only in mechanical and electrical details. In terms of size the roll drive motor is smallest (size 11), and the pitch is largest (size 18). The yaw drive is a size 15. With the exception of roll,

TABLE III SUMMARY OF PROTOTYPE MANIPULATOR DRIVE TRAIN CHARACTERISTICS

Function	Motor	Stall Torque oz-in	Rated Voltage	Peak Current Amps	Gearhead & Ratio	External Gearing	Remarks
Grip	Globe 100A104-9 Type BD, Size 15	1a	27 vDC	8.8	None	3:1 Spur	Brake disengaged upon application of motor power. Brake torque 4 oz-in
	Globe 25A 749 (with brake)	3.4	27 vDC	1.5	None		
Roll	Kearfott R809-25D Size 11 Motor/Tach.	ω 55	Ø 1 115vAC Ø 2 40 vAC 400 cps	0 ω53	Planet A 105A-14 Size 15 165.96:1	8:1 Spur	Tachometer excitation 115 vAC, 0.05 amp Scale factor 0.56 mv/rpm
Yaw	Kearfott T800-36B Size 15 Motor/Tach	1.45	Ø 1 115vAC Ø 2 36 vAC 400 cps	0.11	Planet A 105B-53 Size 15 77.54:1	20:1 Worm	Tachometer excitation 115 vAC, 0.073 amp Scale Factor 2.9 mv/rpm
Pitch	Kearfott V806-36B Size 18 Motor/Tach	2.8	Ø1 115vAC Ø2 36 vAC 400 cps	0.238 0.755	Kearfott C310129-407 Size 18 49:1	120:1 (30:1 Worm x 4:1 Spur)	Tachometer excitation 115 vAC, 0.073 amp Scale Factor 2.9mv/rpm
Extension	Globe 100A379	14	50 vDC	2.8	Planet A105B-42 Size 15 11.73:1	10.7:1 (4:1 Worm x 2.66:1 Spur)	
Elevation	Globe 100A379	14	50 vDC	2.8	Planet A105B-42 Size 15 11.73:1	320:1 (40:1 Worm x 8:1 Spur)	
Azimuth	Globe 100A379	14	50 vDC	2.8	Planet A105B-42 Size 15 11.73:1	300:1 (50:1 Worm x 6:1 Spur)	

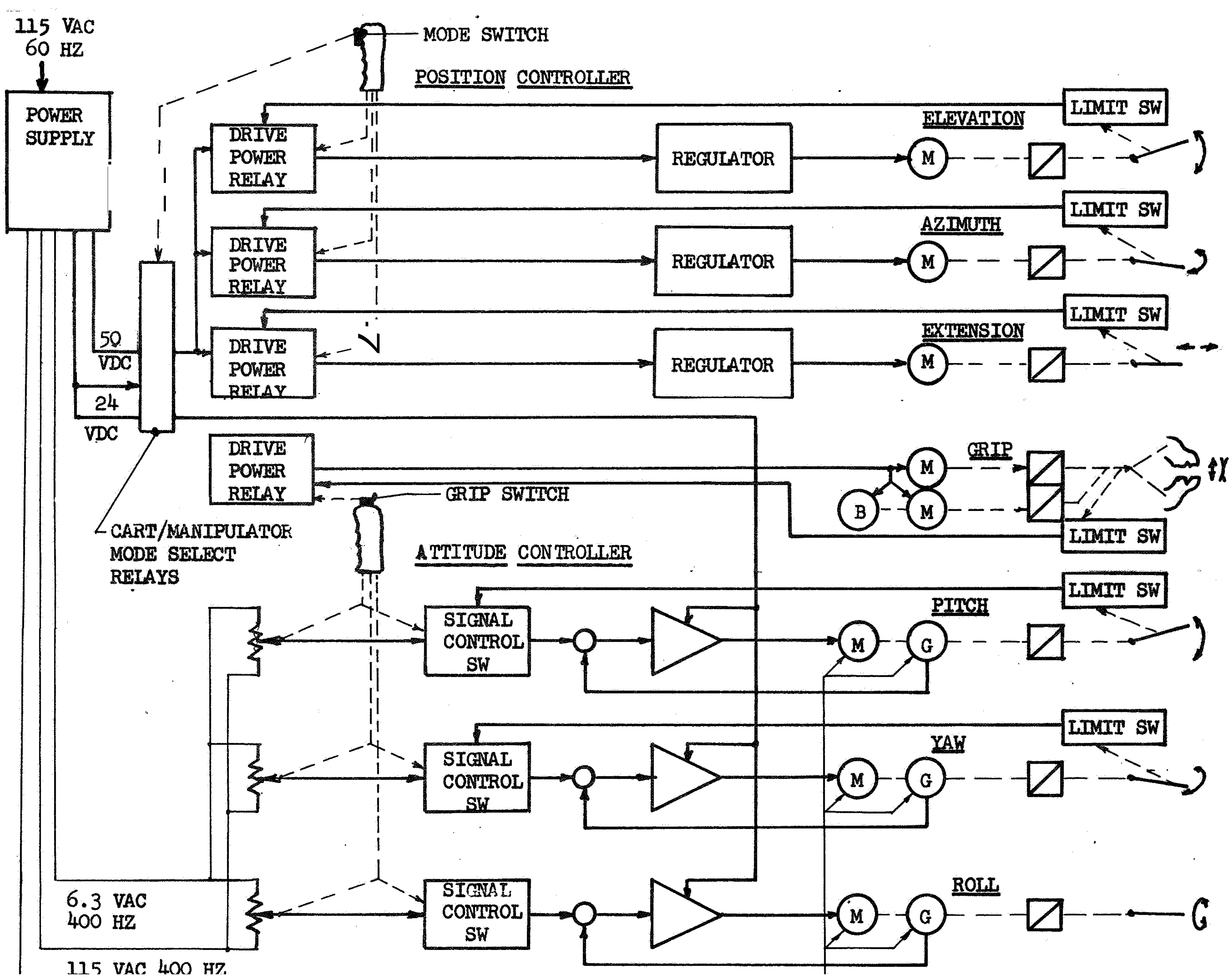


FIGURE 24 FUNCTIONAL BLOCK DIAGRAM OF IMM MANIPULATOR ELECTRICAL SYSTEM

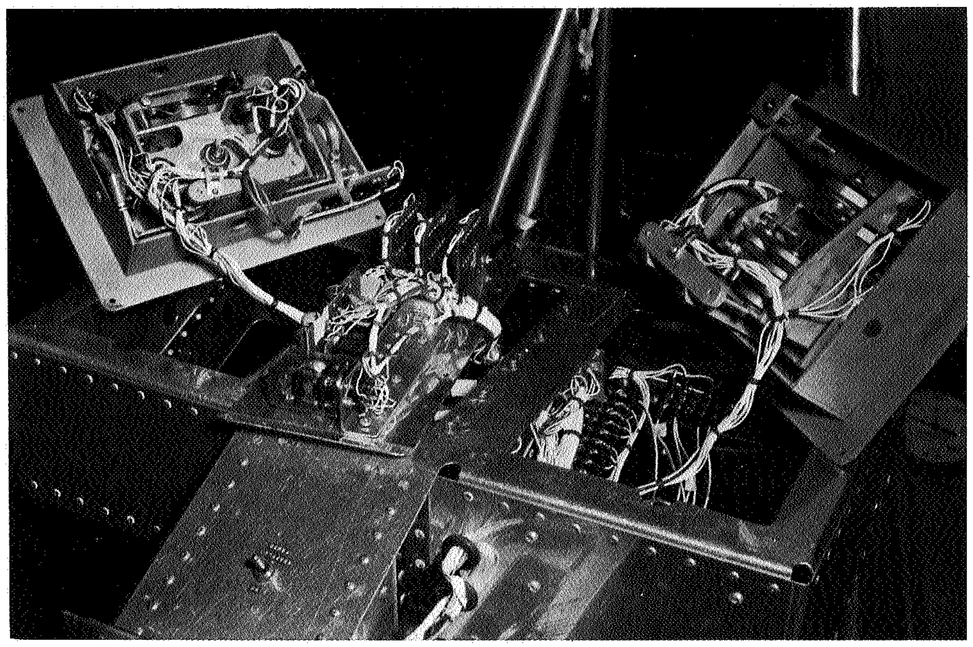
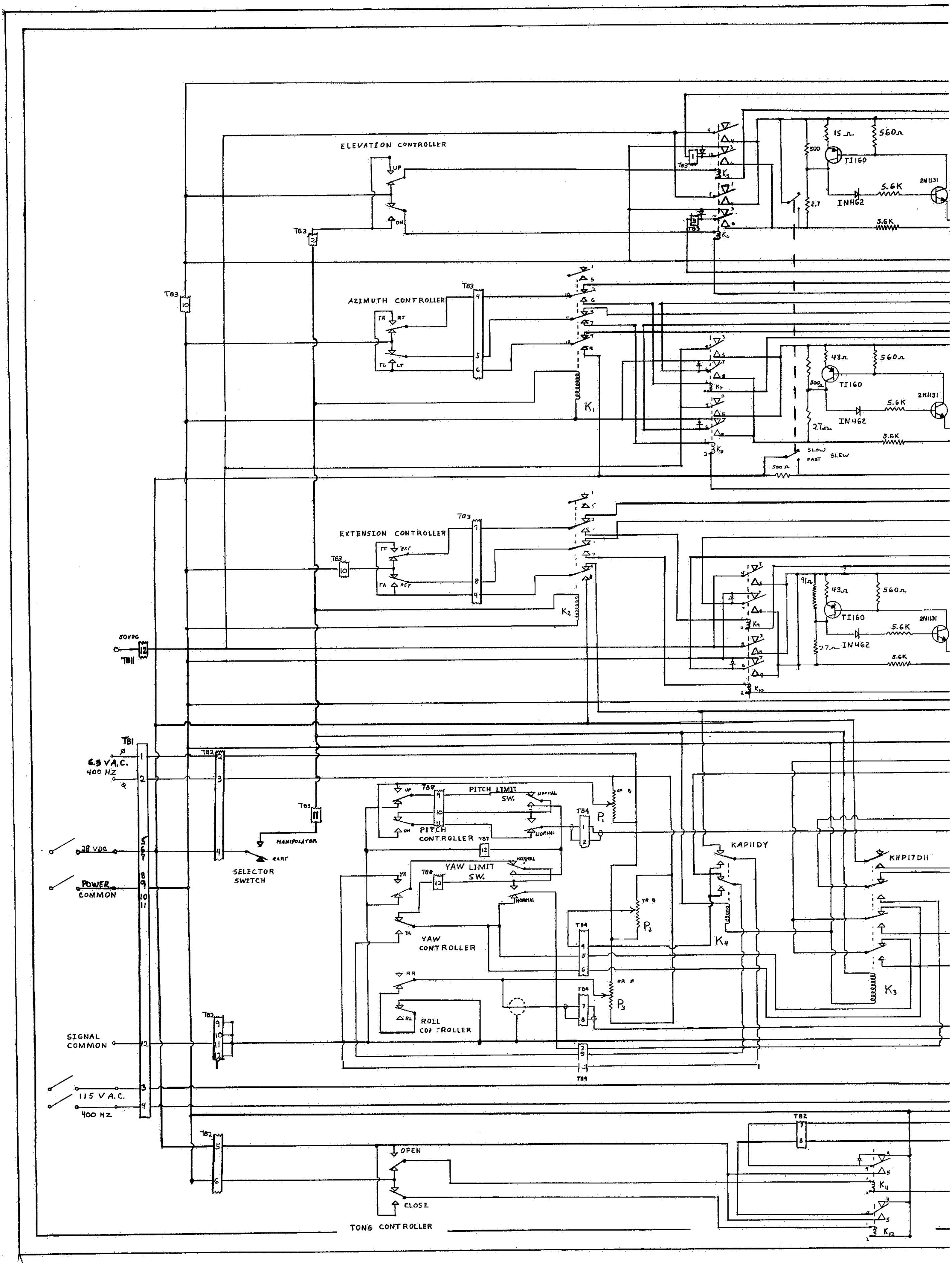


Figure 25 - View of Manipulator/Controller Module with top panels removed, showing under side of controllers and electronics panel. Visible inside the pedestal are some of the terminal boards and associated wiring. In the left foreground is the main power switch for the manipulator electrical system.

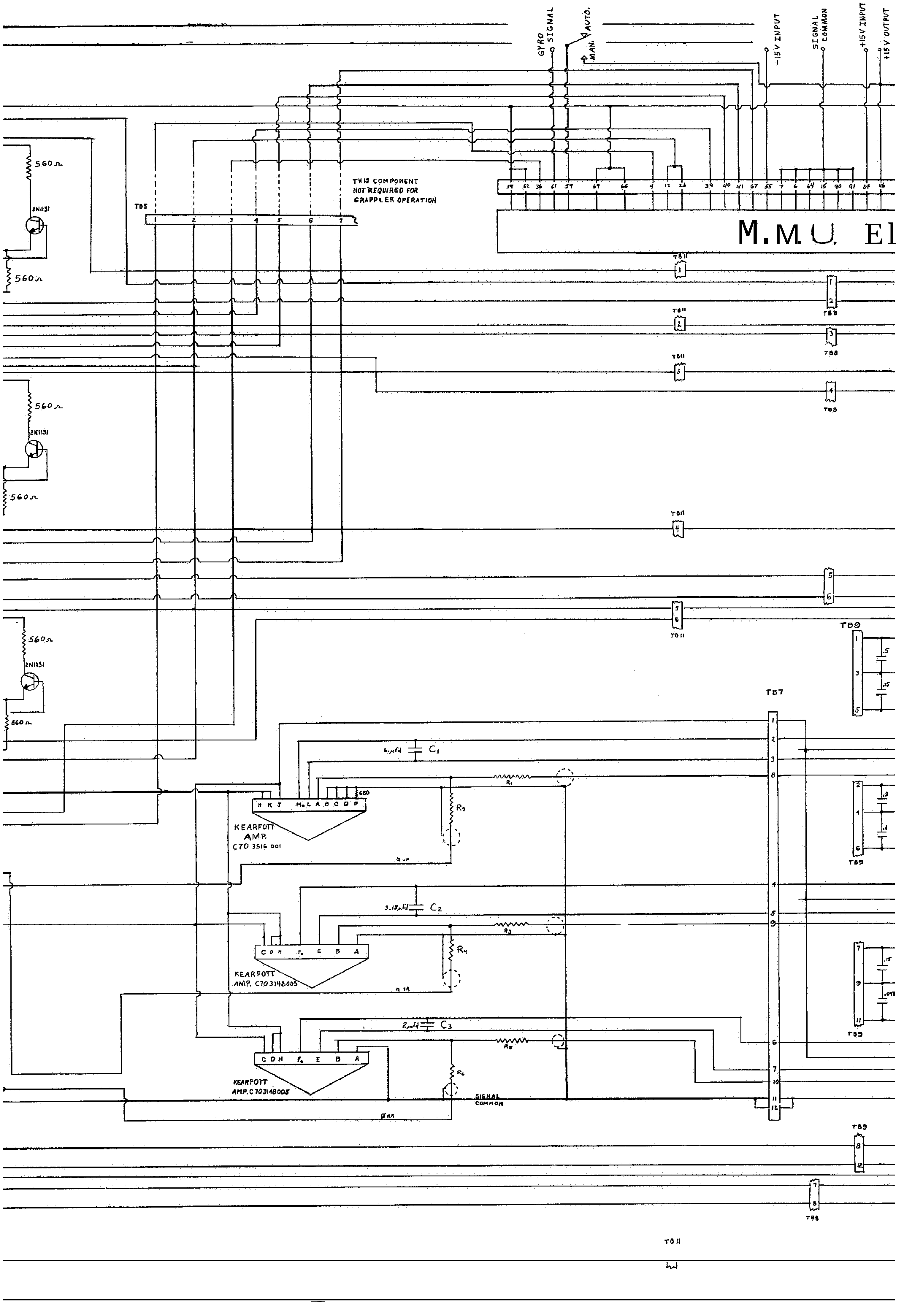
which is a spur gear drive, all drive assemblies consist of a worm gear, external spur gears, a servo gearhead, a servo motor/tachometer, amplifier, signal grounding switches, limit switches, signal summing network, and a potentiometer to generate the proportional commands. The roll drive, provides unlimited rotation about the roll axis, while the pitch and yaw motions are limited as noted below. The ability to modulate the attitude drives enables them to be controlled more precisely than the grosser position drives of the upper arm.

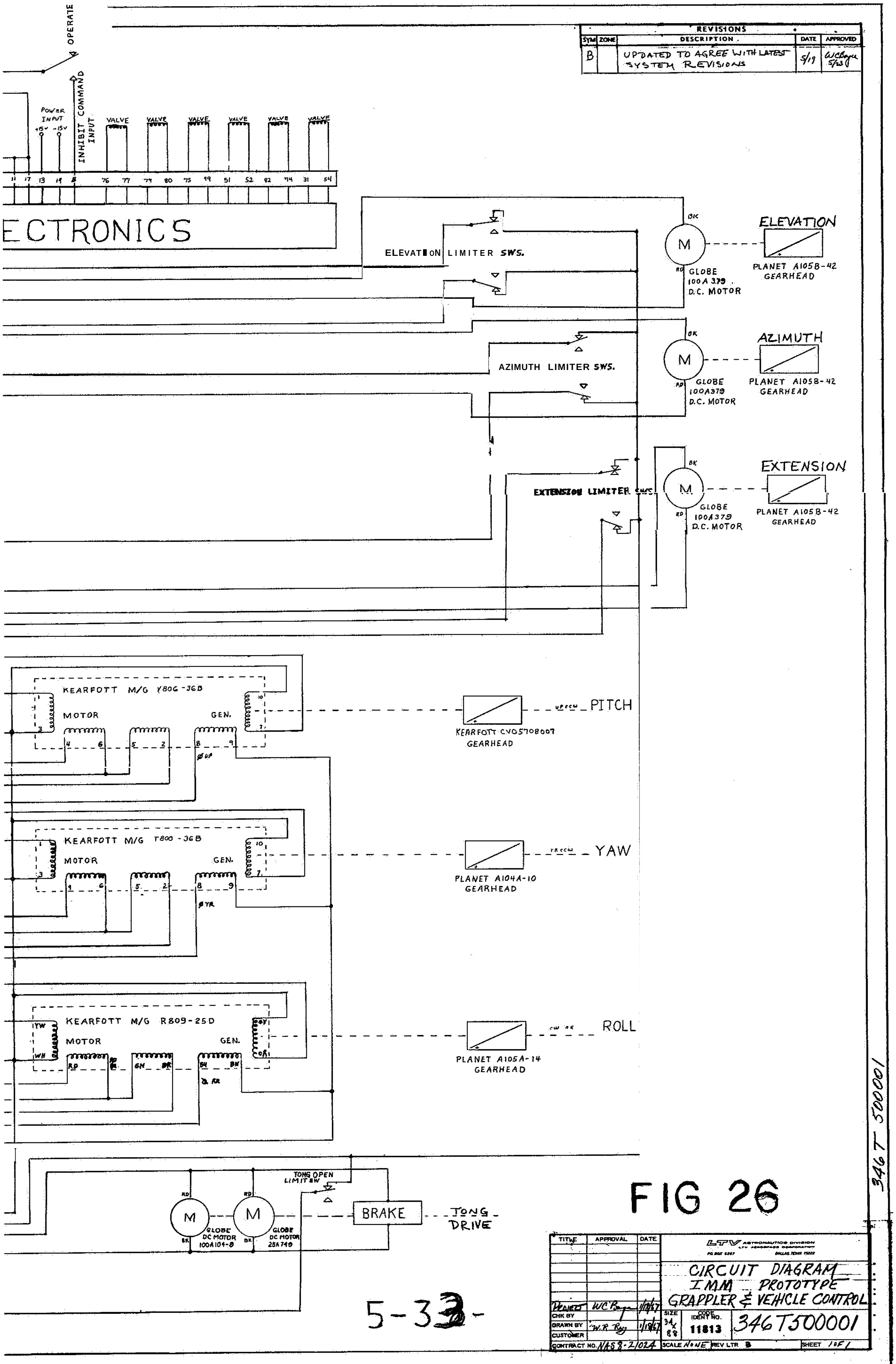
The drive motors are conventional two phase 400 cps servo motors with integral tachometers. The motor fixed phase voltage and the tachometer excitation is 115 volts AC. The motor control phase is driven by a solid state amplifier which provides phase reversible power at an output voltage between 0 and 36 volts AC in response to the amplifier error signal. The error signal is generated by the algebraic summation of the tachometer signal with the command signal from the potentiometer, which has an output level proportional to displacement of the controller from its neutral position. If the tachometer produces a smaller (out of phase) signal than the controller, the amplifier output will increase so as to drive the motor with a higher voltage and thereby speed it up to reduce the error. Strictly the error cannot be reduced to zero, however with the gains available



ELEVATION CONTROLLER
AZIMUTH CONTROLLER
EXTENSION CONTROLLER
PITCH LIMIT SW.
PITCH CONTROLLER
YAW LIMIT SW.
YAW CONTROLLER
ROLL CONTROLLER
TONG CONTROLLER
OPEN
CLOSE
MANIPULATOR
CART
SELECTOR SWITCH
6.3 V A.C. 400 HZ
28 VDC
POWER COMMON
SIGNAL COMMON
115 V A.C. 400 HZ
50VDC
TB1
TB2
TB3
TB4
K1
K2
K3
K4
KAP11DY
KHP17D11
SLOW
FAST
SLEW
TI160
IN462
2N1131
15 Ω
560 Ω
43 Ω
5.6K
500 Ω
2.7
P1
P2
P3

5-32 A


GYRO SIGNAL
AUTO.
MAN.
-15V INPUT
SIGNAL COMMON
+15V INPUT
+15V OUTPUT
THIS COMPONENT NOT REQUIRED FOR GRAPPLER OPERATION
TB5
M.M.U. El
TB11
TB8
TB9
TB7
560Ω
2N1131
C1
C2
C3
R2
R4
KEARFOTT AMP. C70 3516 001
KEARFOTT AMP. C703148005
SIGNAL COMMON



REVISIONS
SYM ZONE DESCRIPTION DATE APPROVED
B UPDATED TO AGREE WITH LATEST SYSTEM REVISIONS 5/19
OPERATE
POWER INPUT +15V -15V
INHIBIT COMMAND INPUT
VALVE
ECTRONICS
ELEVATION LIMITER SWS.
ELEVATION
GLOBE 100A 379 D.C. MOTOR
PLANET A105B-42 GEARHEAD
AZIMUTH LIMITER SWS.
AZIMUTH
GLOBE 100A379 D.C. MOTOR
PLANET A105B-42 GEARHEAD
EXTENSION LIMITER SWS.
EXTENSION
GLOBE 100A379 D.C. MOTOR
PLANET A105B-42 GEARHEAD
KEARFOTT M/G Y806-36B
MOTOR
GEN.
PITCH
KEARFOTT CV05708007 GEARHEAD
KEARFOTT M/G T800-36B
MOTOR
GEN.
YAW
PLANET A104A-10 GEARHEAD
KEARFOTT M/G R809-25D
MOTOR
GEN.
ROLL
PLANET A105A-14 GEARHEAD
TONG OPEN LIMIT SW
GLOBE DC MOTOR 100A104-8
GLOBE DC MOTOR 25A749
BRAKE
TONG DRIVE
CIRCUIT DIAGRAM IMM PROTOTYPE GRAPPLER & VEHICLE CONTROL
TITLE APPROVAL DATE
CHK BY
DRAWN BY
CUSTOMER
CONTRACT NO. NAS8-21024
SIZE
CODE IDENT NO. 11813
346T500001
SCALE NONE REV LTR B SHEET 1 OF 1
346T500001

FIG 26

in the amplifiers being used (500:1-2000:1) errors can be very small, and substantially independent of applied load within the capabilities of the drive motors.

When the controllers are in their neutral position the command signal inputs to the angle drives are grounded. This feature was incorporated to minimize requirements for accurate centering adjustment of the command potentiometers, to reduce mechanical detent repeatability requirements and to provide insensitivity to "noise". In addition, braking action is provided by a signal from the tachometer/generator resulting from any angular displacement of the drive. While this factor is not significant to the yaw and pitch drives, since they are irreversible by virtue of the worm drives, it provides reasonably effective braking of the roll drive when no command is present.

The limit switches in the yaw and pitch drives disable the command signal input, rather than motor power. In each case these drives have limit switches at both extremes of travel. The switching logic is arranged so that the command signals can be applied only *to* move the driven element away from the limit stop.

5.3.4 POSITION DRIVES

The position drives are switched, fixed speed drives, which provide the grosser movements of the arm, namely elevation, azimuth and extension.

The elevation and azimuth drives each consist of a worm gear, spur gears, a servo gearhead, and identical 50 volt permanent magnet, direct current motors. Extension is accomplished by a worm gear driving a rack and pinion. The direction of rotation is controlled as described for the motors in the grip drive. The position drives have limit switches at each extreme of travel similar to that previously described for tongs opening.

The speed for these drives is basically dependent on load and motor characteristics. Some speed regulation is provided by an electronic regulator which shunts a series resistor with a transistor gate as a function of motor current and voltage. As presently configured the regulator is bypassed for the extension drive and for the fast rate condition of elevation drive.

5.3.5 ELECTRICAL POWER SUPPLIES

Three power supplies are provided to permit the user to operate the Experimental Manipulator from a single 60 cps 115 volt AC external power source. The power supplies include a 28 volt DC power supply, a 50 volt DC power supply, and a 115 volt 400 cps inverter power supply. A schematic of these is shown in Figure 27.

The 28 volt AC supply provides grip drive and relay power, and supplies the 115 volt AC 400 cps inverter. Electrically, it is a conventional full wave, center tapped supply, with separate resistor-capacitor filters for the motor/relay power and for the inverter.

The 50 volt DC supply provides the drive power for the position drives. Electrically it is a conventional full wave bridge supply with a resistor-capacitor filter.

The inverter consists of a phase shift oscillator, driver, and push-pull, class B power stage. It supplies the servomotor fixed phase power and tachometer excitation for the angle drives. An auxiliary transformer is provided to generate 6. 3 volt AC center tapped command potentiometer excitation.

5.4 HYDRAZINE PROPELLED TEST VEHICLE

5.4. 1 DESIGN REQUIREMENTS

In order to give the manipulator the most realistic evaluation within reasonable economic limits, MSD-T funded the design and construction of a ground effects vehicle which is propelled by a rocket system closely resembling the actual maneuvering unit propulsion system. The basic design requirements for the vehicle were:

a. Three degrees of control: (1) fore and aft translation; (2) lateral (right and left) translation; and **(3)** yaw (right and left).

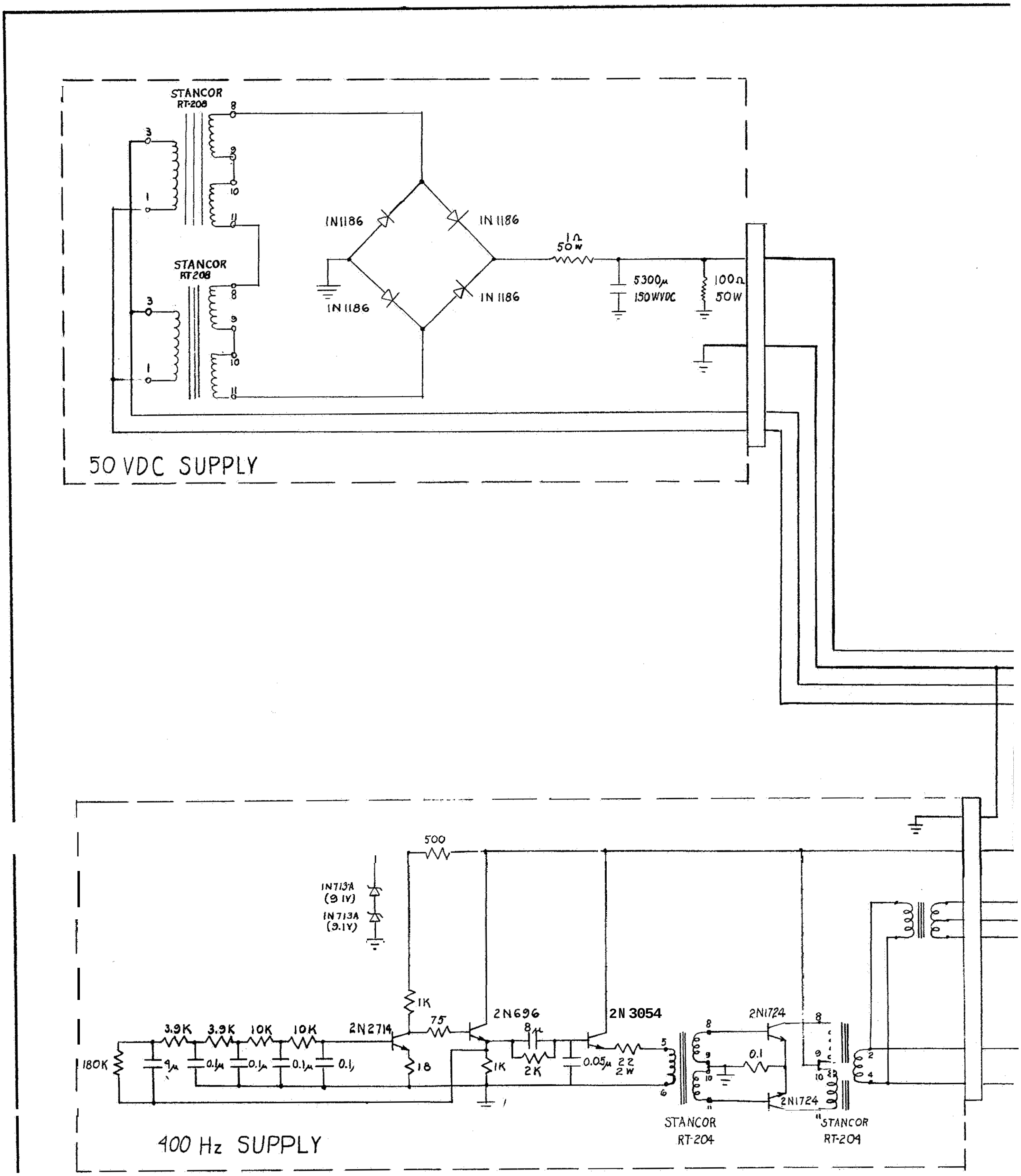
b. Self contained flotation and propulsion systems (no fluid system umbilicals).

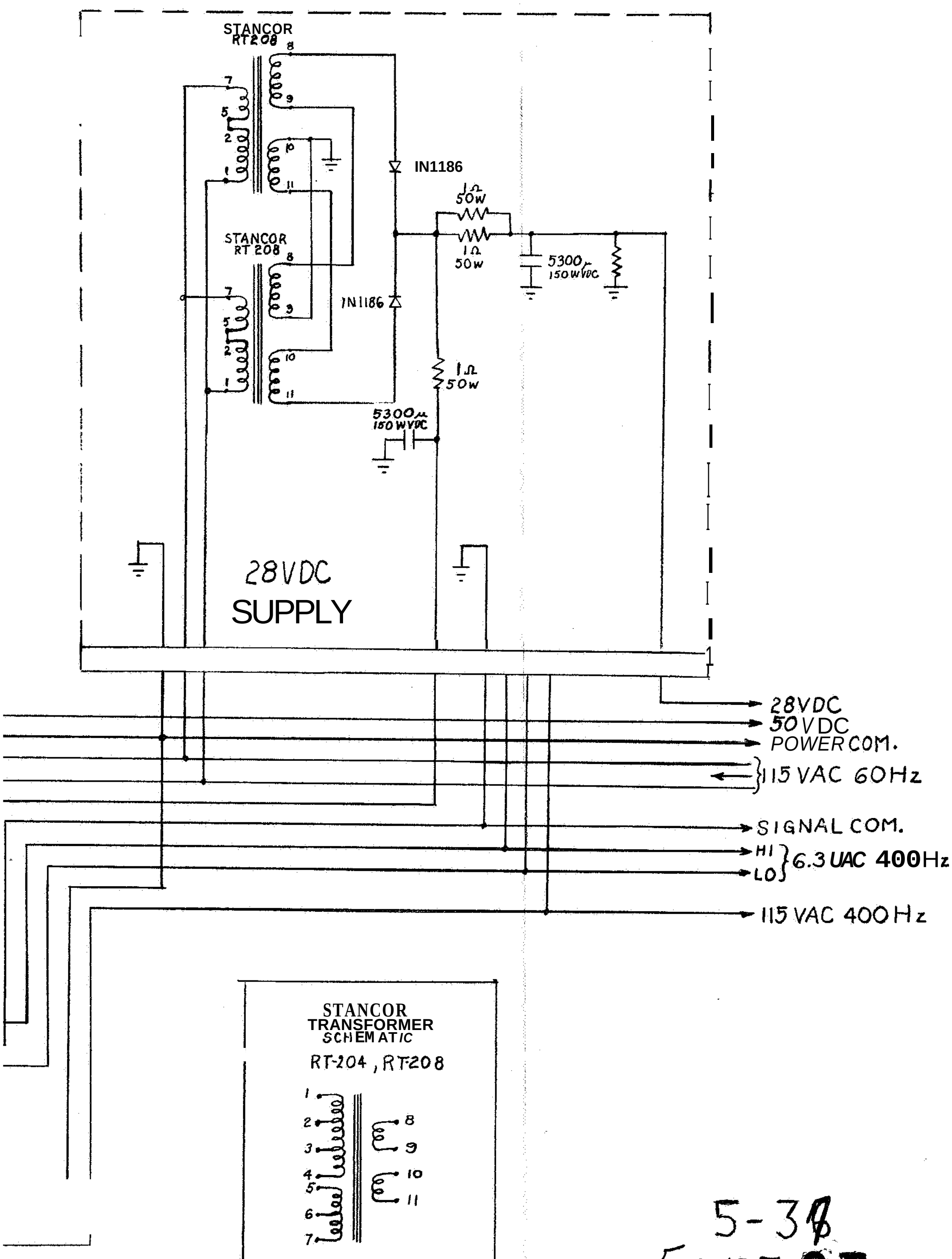
c. Position and relation of the operator to the vehicle similar to that of the Maneuvering Work Platform (MWP).

Procurement lead time and budgetary limitations did not permit optimization of thrust levels and control moments which would duplicate the motion rates and accelerations in translation and yaw which would be expected for the actual space vehicle. However, reasonable simulation of the MWP characteristics was obtained through the selection of propulsion components available either in-house or off-the-shelf from vendors. The resultant system produces adequate control for yaw and fore/aft translation, but is marginal for lateral acceleration.

5.4. 2 DESCRIPTION

Scooter Arrangement - The vehicle shown in Figure 28 was designed to locate the center of gravity at the approximate geometric center


STANCOR RT-208
IN1186
1Ω 50W
5300μ 150WVDC
100Ω 50W
50 VDC SUPPLY
500
IN713A (9.1V)
1K
75
2N2714
2N696
2N3054
3.9K
10K
180K
18
2K
0.05μ
22 2W
STANCOR RT-204
2N1724
0.1
400 Hz SUPPLY



5-38
FIGURE 27

TITLE		DATE	MISSILES AND SPACE DIVISION LTV AEROSPACE CORPORATION P.O. BOX 6267-DALLAS TEXAS 75222		
			SCHEMATIC POWER SUPPLY IMM		
CHK BY	McBean	5/31/67	SIZE 17x22	CODE IDENT NO. 11813	346T500002
DRAWN BY	McBean	5/31/67			
CUSTOMER					
CONTRACT NO. NAS8-21024			SCALE NA	REV LTR	SHEET 1 OF 1

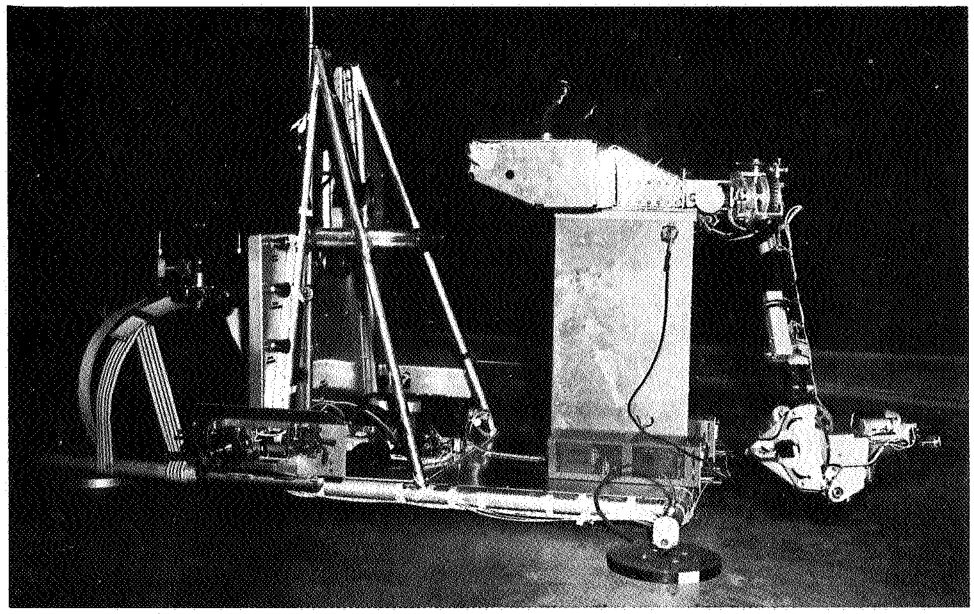


Figure 28 - Side View of Hydrazine Propelled IMM Manipulator Test Vehicle with Manipulator Stowed

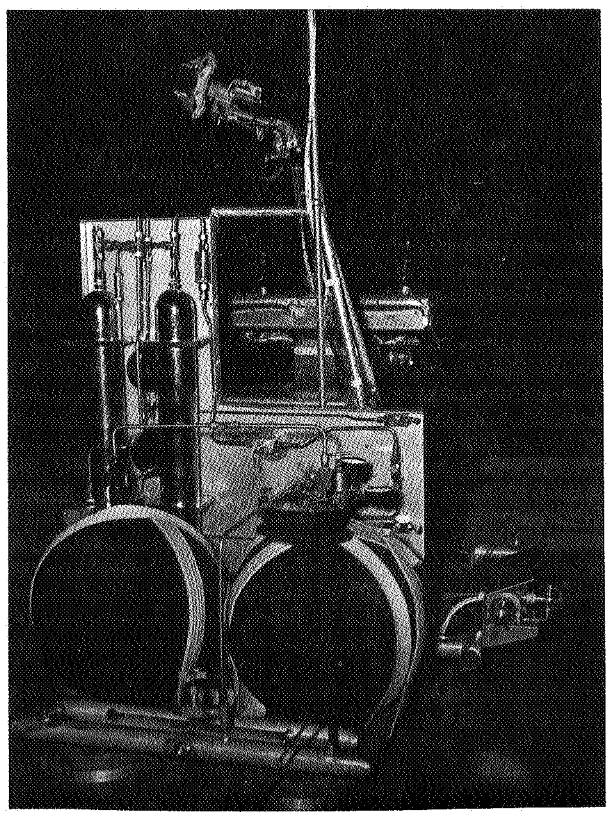


Figure 29 - Back View of Test Vehicle Showing Spherical Air Tanks in Foreground. Mounted on the Seat Bulkhead can be seen portions of the Hydrazine Propulsion System

of the vehicle thus allowing one set of thrust chambers to perform the vehicle maneuvers required for the tests. The subsystems were built in modular form for ease in servicing, maintenance, and mounting. The hydrazine propulsion system, air bearing system, operator's seat, and grappler are the four major assemblies that comprise the docking grappler/manipulator vehicle. The manipulator/controller module is mounted on the forward part of the vehicle frame to provide the maximum swing and reach of the arm. The air bearing system and propulsion system were mounted behind the operator's seat to balance the weight of the manipulator and operator. This arrangement establishes the center of gravity near the geometric center of the vehicle and places the operator and the hydrazine expendables near the CG in order to minimize CG travel resulting from these variable factors.

Air Bearing System - The air bearing system shown in Figure 29 consists of four air pads, two 18 in (45.7 cm) diameter, 2000 psi (13.79×10^6 N/m^2) spherical tanks, an air supply manifold, and a flow control regulator. The air pads were designed to carry 150 lb (667.2 N) each and the total weight of the scooter with operator is approximately 500 lb (2224 N). The air flow to the pads require a constant pressure to prevent scooter bounce. This was accomplished by utilizing the tubular frame of the vehicle to act as a relatively large low pressure manifold. The system provides 30 min of running time without servicing. A minimum safety factor of 2 is provided for the systems; the systems were proof tested to 1.5 times the operating pressures. The flotation of the vehicle is started by opening a manually operated valve admitting flow to the air bearing pads. The air bearings lift the vehicle approximately .02 in (.051 cm) above the floor providing a cushion of air which supports the vehicle. Except for adjustment of the air pad pressure regulator for various vehicle loads, no other control of the flotation system is required.

Propulsion System - Propulsion of the vehicle is provided by a monopropellant hydrazine rocket system having six thrust chambers which serve the dual purpose of propulsion for vehicle translation and for attitude (yaw) control. It is believed that this is the first manned vehicle to use hydrazine as a monopropellant, and the first to be operated in an open laboratory while the laboratory was occupied by assistants and observers without protective clothing. Section 6.1 discusses precautionary measures for personnel safety. The system was chosen for this application to demonstrate its applicability to space maneuvering units and to allow further 'in-house' development of this type of system. Figure 30 is a schematic diagram of the propulsion system. It is a somewhat classical regulated pressure system using nitrogen as the pressurant. Since the vehicle is to be operated in a gravity field and without pitch and roll capability, no positive expulsion device was needed, or provided, in the propellant tanks.

Six 3.7 lb (16.45 N) thrust chambers are arranged in two clusters of three each. The left hand cluster is shown in Figure 31. As shown in

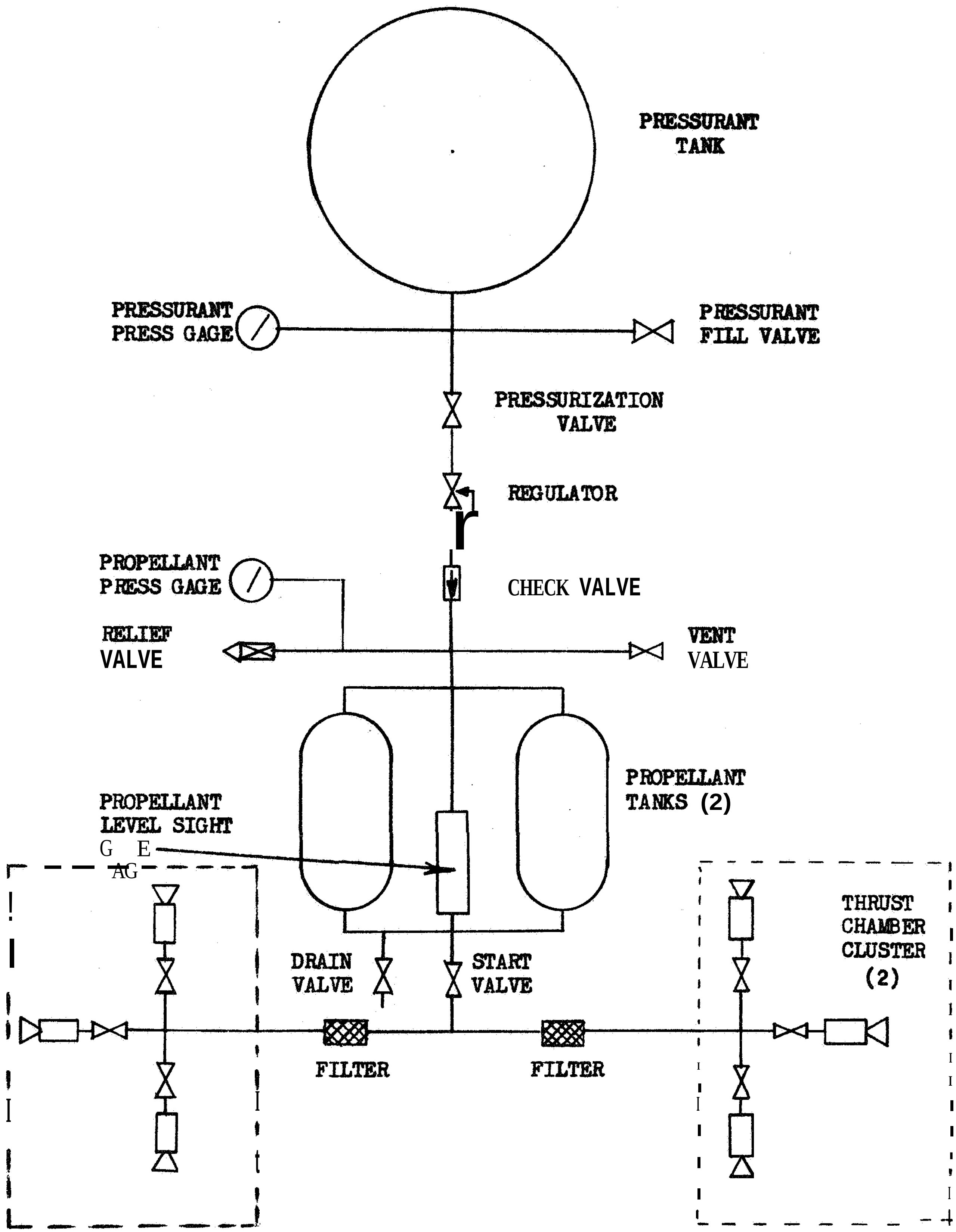


Figure 30 - Schematic Diagram - Hydrazine Air-Bearing Test Vehicle

Figure 32, one cluster is placed on each side of the vehicle at approximately the longitudinal station of the vehicle center of gravity. The thrust chambers are oriented forward, lateral, and rearward. This arrangement provides a total of 7.4 lb (32.9 N) of thrust for fore and aft translation, 3.7 lb (16.45N) of thrust for lateral translation and approximately 22 lb-ft (29.8 N-m) of moment for yaw control. The system uses a mixture of 90 weight percent of hydrazine and 10 weight percent of water for propellant. The two propellant tanks which are used have a usable capacity of sixteen pounds propellant and can provide up to 30 min of normal vehicle operation depending upon the thruster duty cycle. Thrust is controlled by an "on-off" coaxial solenoid valve at the injector of each thrust chamber. Starting response of the thrust chambers is approximately 25 milliseconds from "on" signal to 90 per cent of thrust, and shut-down response is nominally 20 milliseconds. The propellant system is serviced by gravity through a standpipe and funnel. Servicing personnel wear complete protection and self contained breathing apparatus when servicing the system.

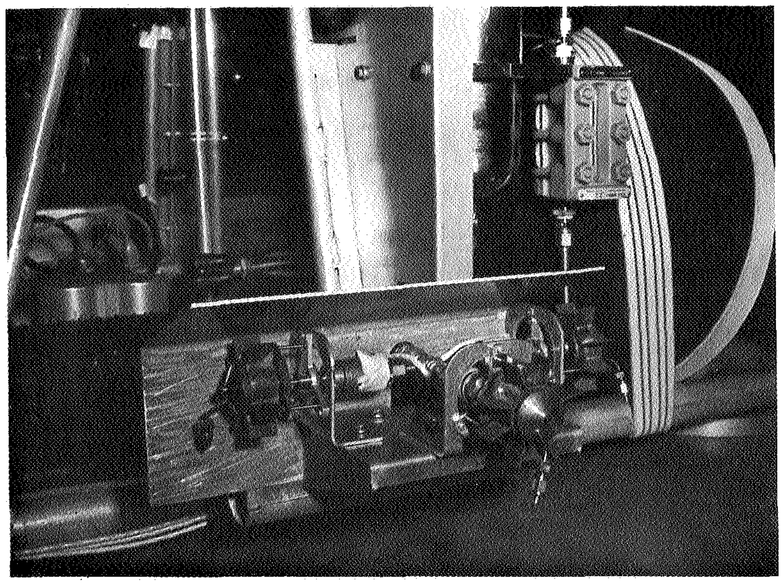


Figure 31 - Left Hand Cluster of Hydrazine Thrust Chambers. Above right is propellant quantity gage. At Right Rear are Propellant and Air Tanks. Note Protective Blast Shield behind thrusters.

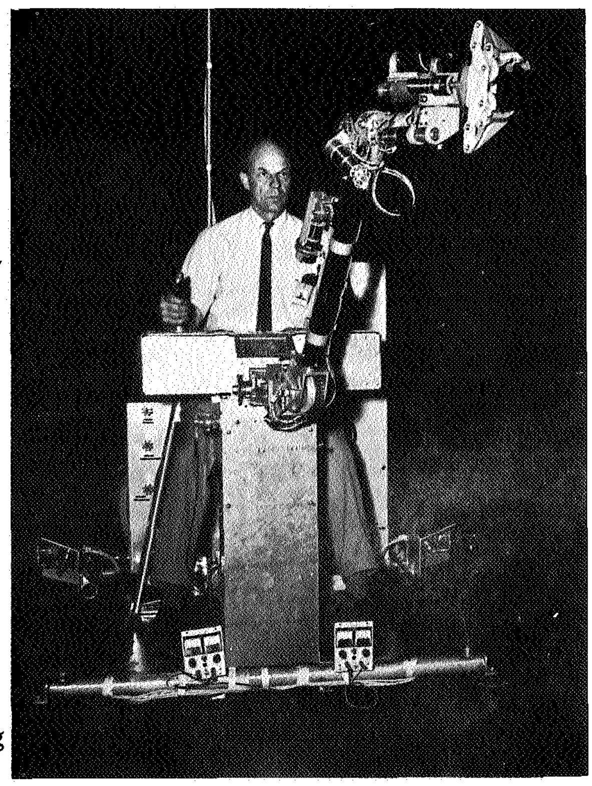


Figure 32 - Front View of Test Vehicle Showing Right and Left Clusters of Thrust Mast in background is support for overhead electric power cable.

5.5 WEIGHT SUMMARY (actual unless otherwise indicated)

R. H. Controller	6. '81		
L. H. Controller	6. 28		
Control Console Pedestal (Inc. Azimuth Pivot)	28. 58		
Electrical Power Supplies	35.00	est.	
Fixed Weight			76.67 lb (341 N)
Upper Arm (elbow to Azimuth Pivot)	24. 15	(1)	
Lower Arm (Tongs to elbow)	11. 28	(1)	
	35.43	(1)	
Motor and Gear Train Mods	5.00	(2)	
Movable Weight			40.43 lb (180 N) est.
Vehicle Structure	20. 00	est.	
Air Pads	15. 00	est.	
Propulsion System (Dry)	90.00	est.	
Propellant	16.00		
Air Tanks charged	80.00	est.	
Scott Air Pack	15. 00	est.	
			236 lb (1050 N) est.
Operator (Nominal)			180 lb (802 N) est.
Test System Total Weight (Nom)			533. 10 lb (2373 N)

(1) Note these were actual weights prior to motor and gear train modifications.

(2) Estimate 5 lbs. added by modification.

6.0 TEST AND EVALUATION PROGRAM

The end objective of the current IMM Contract Task Addendum is the simulation testing of the rate command docking/anchoring manipulator. This objective was achieved by conducting manned testing, utilizing MSD-T frictionless platform facilities to simulate relative vehicle/worksite motions. The planning and conduct of the simulation testing, and a presentation of the test results is contained in the following paragraphs.

6.1 TEST PLAN

6.1.1 OBJECTIVES

The test objectives of the manned testing phase utilized the Maneuvering Unit Systems Test Laboratory (MUSTL) frictionless platform facilities in order to evaluate the following:

(a) An experimental version of a non-bi-lateral rate command grappling manipulator to verify the versatility of the overall mechanism in accomplishing representative docking, grappling and anchoring functions.

(b) The feasibility of using a shared control concept in which the vehicle and the manipulator are each controlled in six degrees of freedom by selective use of one set of controllers.

Specific objectives of the test program were to determine and verify:

(a) The adequacy of the basic grappler configuration and motions for performing docking and anchoring.

(b) The desirability of controlling grappler movements in six degrees of freedom with spacecraft type translation and attitude controllers, using rate commands.

(c) The feasibility of anchoring to various targets without force feedback.

(d) The suitability of the "arm" and "wrist" servo drive rates designed into the unit.

(e) The feasibility of time-sharing the controls with the "spacecraft".

(f) The adequacy of the tongs design for anchoring to various objects.

A biproduct of this testing, which prompted MSD-T to build the hydrazine-propelled test vehicle, was to gain in-house experience in the use and handling of monopropellant hydrazine.

6.1.2 FACILITY REQUIREMENTS

A number of modifications to the existing Maneuvering Unit Systems Test Laboratory (MUSTL) frictionless platform facility were required. In order to permit testing using a hydrazine propulsion system in an enclosed area surrounded by office and shop personnel, precautions had to be taken to minimize the hazards due to fire and toxicity. Major items of concern were the toxic properties of hydrazine, fire potentials, propellant spills, and exhaust products of the hydrazine thrusters.

The polished MUSTL air-bearing working surface, shown in Figure 33, is approximately 39 ft (11.6 m) in diameter, and is contained in a large fireproof room approximately 90 ft by 140 ft (27.5 m by 42.7 m). To provide a safe working environment for the test operators and adjacent areas, a high-volume ventilating system was added to the MUSTL area for removal of the hydrazine vapors and engine exhaust gases (hydrogen and ammonia). In order to accomplish this requirement, an 86,000 cfm (40.6 m^3/sec) exhaust system was installed in the ceiling and the air bearing working surface was enclosed with a 50 ft by 80 ft (15.3 m by 24.4 m) roll-up fire proof curtain wall. The wall is open at the bottom to allow fresh air to enter and flush the working surface of all vapors. The exhaust system provides an air change once each minute.

Fire hoses were installed to provide fire protection and propellant spill wash down. A drain ditch was installed around the periphery of the air bearing working surface which drains into a 4 ft by 7 ft by 6 ft (1.2 m by 2.1 m by 1.8 m) catch basin. The catch basin in turn drains into the plant waste system.

Wash down capabilities for the operation personnel was provided by the installation of a safety shower and eye wash, as shown in Figure 34. In addition, during servicing the service technician was clothed in protective clothing, with neoprene rubber boots and gloves, with face mask and protective self-contained breathing air supply. During conduct of most of the tests, the test operator was provided with a mask and self-contained breathing air supply in the event of a high residual concentration of ammonia fumes. He also wore neoprene rubber boots to preclude injury due to inadvertent impingement of the thrusters upon his legs.

6.1.3 EQUIPMENT REQUIREMENTS

To achieve the objectives of this test program, the prototype manipulator was mounted on the hydrazine-propelled air bearing test vehicle described in Section **5.4,** and shown in additional detail in Figure 35 and 36. To test the feasibility of anchoring to objects of various shapes and with

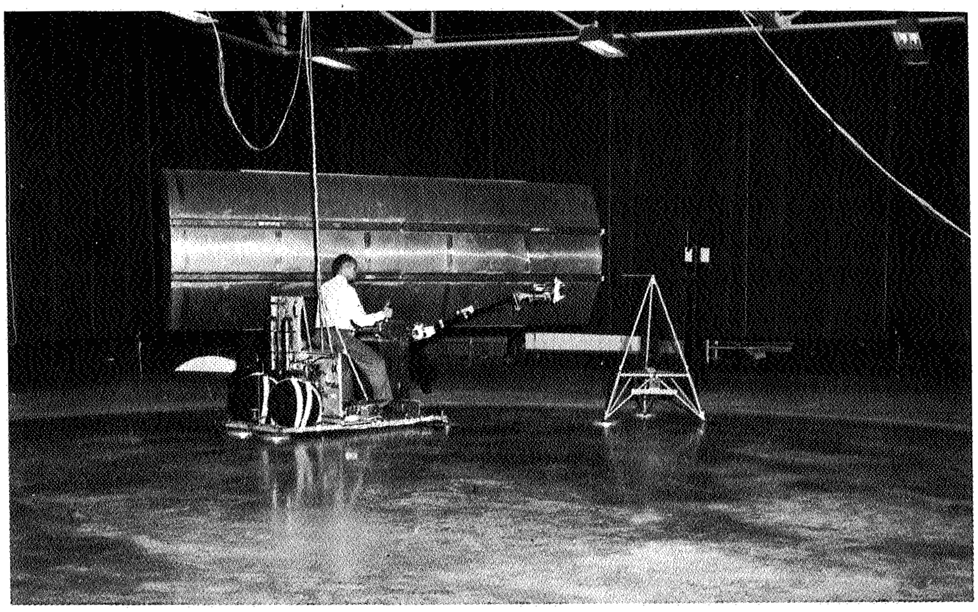


Figure 33 - IMM Manipulator Anchoring Tests Being Performed on Frictionless Platform. Note Sixth Degree Target at Left and Air-Bearing Tripod Target at Right.

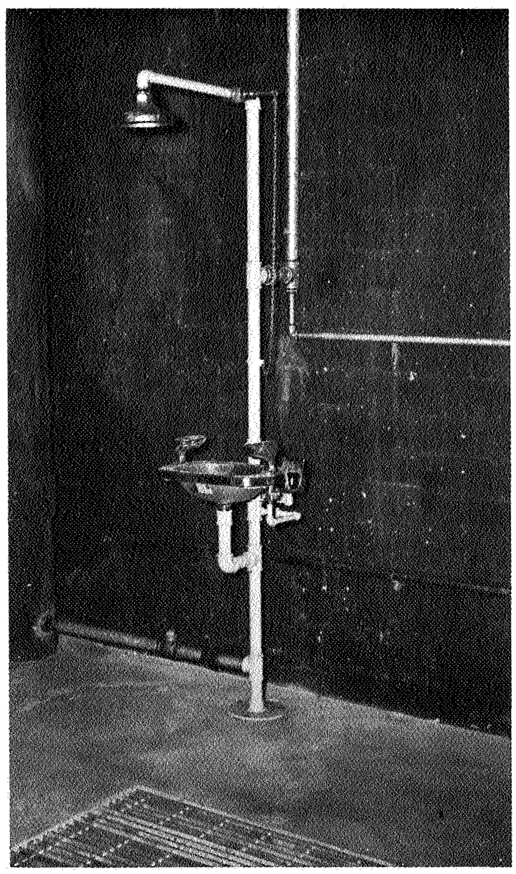


Figure 34 - Safety Shower Installed for Hydrazine Tests

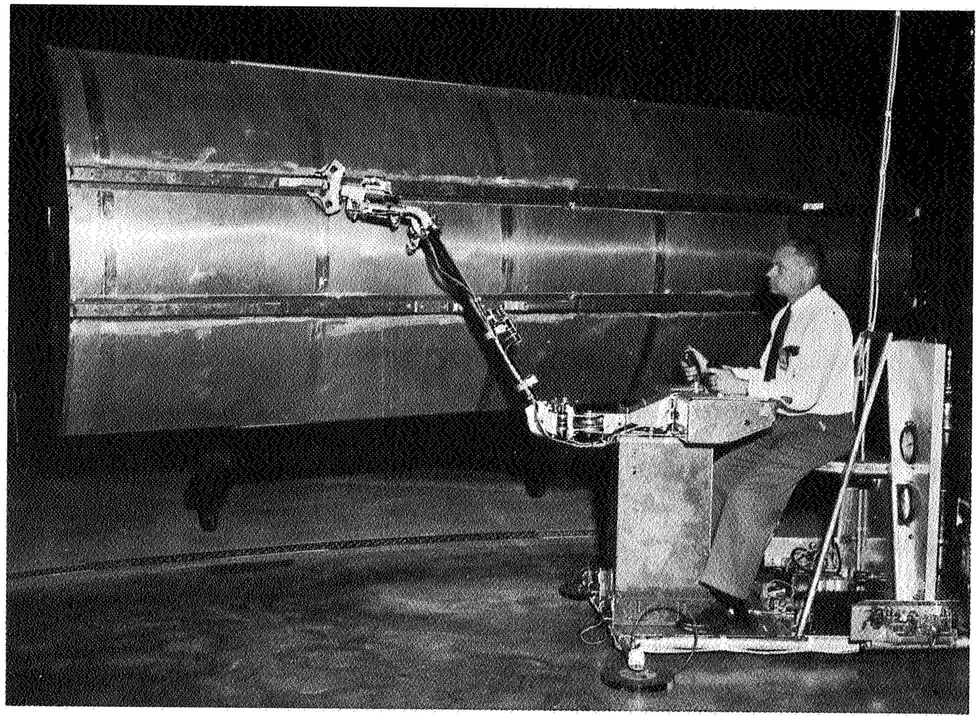


Figure 35 - IMM Prototype Grappler Mounted on Air Bearing Test Vehicle Shown Anchoring to Sixth Degree of Freedom Frame

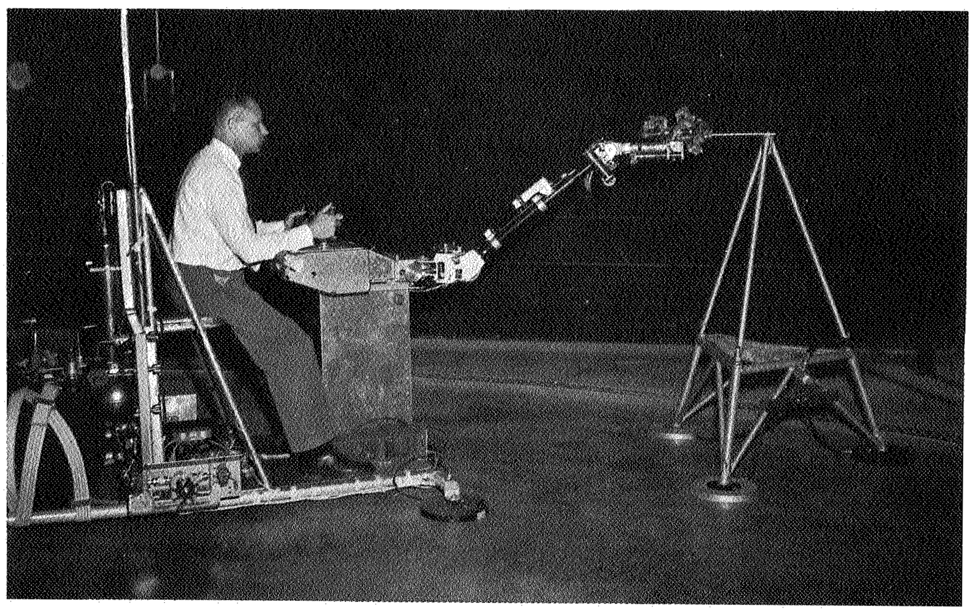


Figure *36* - IMM Prototype Grappler on Air Bearing Test Vehicle Shown Anchoring to Third Degree of Freedom Mass Handling Tripod differing size, mass and behavior of motion, two anchoring target adapters were employed, one a tube and the other a trailer hitch ball. These were then mounted on two different target vehicles. The first of these is a fixed-base Sixth Degree of Freedom Frame (see Figure 35), which has a balanced four-bar linkage to permit the target to move vertically when disturbed. The second target, known as a Mass Handling Platform, is a tripod air-bearing device, which represents small target vehicles. This device, shown in Figure 36, has three degrees of freedom in the horizontal plane (longitudinal and lateral translations, and yaw), permitting it to move freely when disturbed.

6.1.4 TEST PROCEDURE

The test program consisted of five basic test situations which are summarized in Table IV. Each test involved controlling the test vehicle in a 90 deg yaw maneuver, translation across the frictionless platform surface to the vicinity of the docking target, deployment of the manipulator from a stowed position, and anchoring to the target adapter. While the basic maneuvers were similar in each test, the initial and final conditions required different maneuver profiles. For example, if head-on docking was required, the initial vehicle orientation was yawed 90 deg to the target. If side docking was required, the initial vehicle orientation was head-on to the target.

TABLE IV GRAPPLER ANCHORING TEST SUMMARY

TEST NUMBER	TEST DESCRIPTION	INITIAL CONDITIONS
1	Head-on Docking with tube on Sixth degree frame	Grappler Stowed Vehicle at "Start", Yawed 90 deg to Target
2	Side Docking with tube on Sixth degree frame	Grappler Stowed Vehicle at "Start", Head-on to Target
3	Head-on Docking with Ball on Sixth degree frame	Grappler Stowed Vehicle at "Start", Yawed 90 deg to Target
4	Head-on Docking with Ball on Mass Handling Platform	Vehicle at "Start", Yawed 90 deg to Target Grappler Stowed
5	Side Docking with Ball on Mass Handling Platform	Vehicle at "Start", Head-on to Target Grappler Stowed

Three test subjects were employed, and after a familiarization period, each subject was given three trial runs for each of the five tests. Figure **37** shows a typical run profile for each test subject. Each trial was recorded on a form similar to that shown in Figure **38.** During each run, the test engineer recorded running time, time from start of run to initial rendezvous, the observed maneuver pattern, and the proficiency of the operator. Initial rendezvous is defined as that time when the operator ceases his approach maneuvers and begins his anchoring maneuvers. An attempt was also made to record the number of times the test subject switched back and forth between the grappler controls and the vehicle controls. However, this was difficult to ascertain from observation alone. An approximate number of changeovers was attained during post run debriefings by combined estimates of the test subject and the test observer.

It may be seen from Figure **37** that ten minutes was allotted for each trial run, with short, intermediate debriefings. At the end of each allotted 30 minutes of running time, a 30 minute refill period was scheduled to permit servicing of propellant and compressed air. This also provided a break between tests.

6.2 TEST RESULTS

The tests of the IMM prototype grappler were conducted in general accordance with the foregoing plans without serious episode. The tests were highly successful, and all test objectives were achieved. Test data taken during runs, and observations obtained from debriefings, have been tabulated, and are presented in Appendix I.

Testing proceeded smoothly, with test runs being completed in far less time than allocated. Whereas ten minutes was originally allocated for each trial run (Figure 37), actual trials were completed in most cases within one to four minutes each. The fact that run time was reduced meant that less propellant was used than originally anticipated, and the total time on each hydrazine engine was reduced. All tests were completed using 100 lb (453.6 N) of hydrazine, which averaged approximately 680 sec of operation for each engine.

This latter fact is significant in view of earlier difficulties encountered prior to the start of testing. During initial shakedown prior to testing, erratic operation of one of the thrusters was encountered. Subsequent investigation revealed that degradation of the catalyst had occurred in several of the engines, necessitating their return to the vendor. All six thrusters were refurbished by the vendor and returned to MSD-T, together with recommendations for extending engine operating life. In addition to repacking the catalyst beds, a new upper catalyst bed design was incorporated. However, due to the design and construction of these developmental thrusters, no simple, quantitative technique exists for detecting and measuring catalyst

Test Subject:

OPERATION		ALLOTTED RUN TIME	DEBRIEF	REFILL
FAMILIARIZATION		20	10	
BREAK				30
TEST #1	TRIAL #1	10	5	
	TRIAL #2	10	5	
	TRIAL #3	10	10	
BREAK				30
TEST #2	TRIAL #1	10	5	
	TRIAL #2	10	5	
	TRIAL #3	10	10	
BREAK				30
TEST #3	TRIAL #1	10	5	
	TRIAL #2	10	5	
	TRIAL #3	10	10	
BREAK				30
TEST #4	TRIAL #1	10	5	
	TRIAL #2	10	5	
	TRIAL #3	EI	10	
BREAK				30
TEST #5	TRIAL #1	10	5	
	TRIAL #2	10	5	
	TRIAL #3	10	20	30

Figure 37 TYPICAL RUN PROFILE FOR EACH TEST SUBJECT
(NOTE: $\boxed{x}$ is time in Minutes)

<table>
<tr><td rowspan="2">TEST
SUBJECT</td><td colspan="2">NAME</td><td colspan="2" rowspan="2">TEST TITLE
Head-On Docking with Ball on
6th Degree Frame</td><td>TEST
NO. 3</td></tr>
<tr><td colspan="2">EXPERIENCE</td><td>TRIAL
NO.</td></tr>
<tr><td colspan="3">INITIAL CONDITIONS
Grappler Stowed
Vehicle at "Start" Point, Yawed 90° to Target</td><td colspan="3" rowspan="2">FINAL CONDITIONS
Dock Head-On with Ball
1 7/8" D Ball Mounted on 6th Degree Frame
Feet above Floor</td></tr>
<tr><td colspan="2">Start Time</td><td>Finish Time</td></tr>
<tr><td colspan="2">TEST
ENGINEER</td><td>TIME TO
INITIAL
RENDEZVOUS</td><td colspan="2">NUMBER OF
CONTROL
CHANGEOVERS</td><td>TOTAL
RUN
TIME</td></tr>
<tr><td colspan="3">OBSERVATIONS BY TEST ENGINEER
Flight Profile:

General:</td><td colspan="3">OBSERVATIONS BY TEST SUBJECT
Ease of Operation:

Use of Modulation:

General:</td></tr>
<tr><td colspan="6">REMARKS</td></tr>
</table>

Figure 38 SAMPLE FORM FOR RECORDING TEST RESULTS

degradation, and thus, of predicting engine life. Inasmuch as it was not known at that time how many seconds of engine operation would be required to complete the contract testing, a number of precautions were taken to extend thruster life:

(a) Prior to cold motor starts, a vacuum was applied to motors to reduce moisture and volatile contaminants within the catalyst, to avoid generation of high pressure gases within the catalyst during starts.

(b) A warm-up procedure to avoid cold starts was established.

(c) Use of cooling fins on the motors was continued to maintain lower motor injector temperatures, so as to avoid high temperature starts.

(d) Additional precautions were taken to avoid running out of propellant during testing, which produces thermal shock in the catalyst beds.

Based upon the design improvements incorporated in the motors, and with strict adherence to the foregoing precautions, the vendor predicted that motor operating times of from 2000 seconds to 4000 seconds should be possible. The recommended procedures were closely adhered to, since it was imperative that testing of the IMM grappler be completed without additional engine failures, and no further difficulty was encountered.

It was originally intended that testing of the manipulator docking functions be conducted utilizing automatic yaw attitude stabilization on the vehicle. This was to be attained through the use of a control electronics package and rate gyro made available by the contractor from another source. At some undetermined point in the installation and preliminary checkout of the manipulator/vehicle control system, it is believed that the control electronics package was subjected to a voltage overload which burned out a portion of the control logic circuit. Inasmuch as this equipment was part of the test vehicle system, and not a deliverable end item, and in view of the fact that the electronic malfunction may have been contributory to the malfunction of the propulsion thruster, it was decided to continue the testing without utilizing automatic yaw attitude stabilization. As a result all tests were conducted with open-loop yaw attitude stabilization.

Despite certain limitations inherent in frictionless platform testing, the tests clearly indicated that the experimental version of the rate command grappling manipulator is a highly versatile mechanism, and was capable of accomplishing the representative docking / grappling functions. The results also verified the feasibility of using a selectively shared control system, common to both the grappler and the test vehicle. Nevertheless, caution must be exercised in extrapolating these results to apply to space situations involving many more degrees of freedom.

It was evident during testing that absence of automatic yaw stabilization made the control task more difficult, necessitating constant switching back and forth of control between vehicle and grappler. This factor undoubtedly contributed to the confusion of controls in a number of cases, wherein grappler control was commanded when vehicle control was desired and vice versa.

It is of interest to note at this point that in the absence of yaw stabilization, a control technique different from that originally anticipated was employed to accomplish docking. The original intent was to approach the target and position the vehicle for docking, allowing the automatic system to maintain a stabilized attitude while maneuvering the grappler to grasp the docking target. With open-loop yaw control, it was found to be easier to deploy the manipulator to an approximate position for docking during the approach run, and then fly the vehicle to accomplish the dock, making only minor readjustments of the grappler.

In support of the validity of the original docking concept, associated informal tests demonstrated that, with angular and linear rates between vehicle and target nulled out, a high degree of grappling dexterity could be attained with the manipulator. This fact leads one to the tentative conclusion that with automatic attitude stabilization about three axes, orbital docking and anchoring could be achieved, providing relative rates of motion between vehicle and target can be essentially nulled. This may, however require increasing available rates of manipulator motion to enable chasing a moving target.

Following familiarization, all three of the test subjects were able to accomplish all of the basic tests, although with varying degrees of proficiency. Dexterity in the use of the rate command manipulator definitely increases with practice, but practice in the use of the manipulator alone (that is from a non-moving base), did not always lead to more proficient accomplishment of the docking task on a moving base. Nevertheless, Test Subject C, who had had the most practice with fixed operation base of the manipulator, did in most cases make the best time scores in the docking attempts. Test Subject **A**, however, displayed better technique in maneuvering the vehicle.

Docking to the 4-bar Sixth Degree of Freedom frame was accomplished with approximately the same degree of ease as with the Mass Handling tripod. However, once disturbed the larger mass moved in a more predictable path. In general it can be stated that head-on docking to either target is easier than side docking, and that head-on docking to the tubular target was easier than docking with the ball, requiring less precision. Side docking with the ball is more difficult than with the tube due ***to*** the greater precision requirement.

One reason for the greater difficulty in accomplishing side docking lies in the low lateral thrust level on the test vehicle. The 3.7 lb (16.45 N) lateral thrust (as compared with 7.4 lb (32.9 N) fore and aft) made lateral translation and control difficult. It cannot therefore, be categorically stated that side docking per se is more difficult than head-on docking, but only as it applies to this particular test situation.

With regard to specific objectives of the tests, the following comments are presented

(1) The basic grappler configuration and motions are adequate to perform the simulated test missions. Although not mandatory, increasing the up pitch angle to 90 deg appears to be desirable, as would an increase in available extension. It also appears that, in certain situations, a total extension travel of approximately 24 in (.61 m) might be useful. This is especially true if the manipulator is to be maneuvered from a fully stabilized vehicle; since it would require less maneuvering of the vehicle.

(2) Control of grappler movement with spacecraft translation and attitude controllers, using rate commands is very desirable, within the bounds of the simulated mission tests. In view of the necessity for constantly switching back and forth between vehicle and manipulator controls, it is believed that the operator would be unable to accomplish the task with separate vehicle and manipulator controllers. This would probably be even more difficult if the controllers were of different types, requiring operator adaptation at each switchover. The fact that the control movements for command of the manipulator correspond generally to the control movements for vehicle control greatly simplifies the control task.

Some test subjects encountered difficulty in operating the left-hand controller, due primarily to the small motions needed to obtain switch closure. This often resulted in inadvertent cross-coupling of commands. Some improvement could be obtained by allowing more pre-travel of the control grip prior to switch actuation and/or by increasing the control breakout force. However, if rate modulation is added to the left-hand controller as recommended in paragraph (4) below, the left-hand controller will undoubtedly prove to be as easy to operate as the present right-hand controller.

(3) No problem existed in any of the anchoring tests due to lack of force feedback. However, if the versatility of the grappler is to be expanded to include manipulative tasks, the requirement for force feedback should receive further study.

(4) The drive rates of the wrist and arm servo drives are generally satisfactory for the simulated tests performed, but the ability to obtain more precise movements of the upper arm would be highly desirable. Also, in view of the difficulty encountered in capturing a moving target, an increase in the rates of motion would be helpful. It is recommended therefore, that in future designs all grappler motion rates be increased approximately 50 per cent, and that modulation of rates be applied to all motions including the gross arm movements.

(5) The feasibility of selectively sharing the same controls between manipulator and vehicle has been discussed in (2) above.

(6) The grappling tongs as originally designed were marginally satisfactory for gripping fixed objects from a fixed base vehicle. However, for accomplishing the docking tasks from a moving vehicle the width of the jaws was too narrow, requiring very precise positioning of the jaws. A simple "fix", involving the addition of two angles to the sides of one jaw member, had the effect of doubling the width of the tongs. This greatly simplified the docking task, while preserving the adaptability of the tongs to a variety of shapes. As presently configured the tongs are believed to be completely satisfactory for the task of anchoring to a variety of objects.

Visibility of the target during the anchoring operation must be commented upon at this time. Due to the grappler wrist configuration small objects are hidden from sight if a head-on grappling approach is used. However, the simple expedient of yawing the wrist between 30 to 45 degrees solves the visibility problem without sacrificing any anchoring dexterity.

In addition to determination and verification of the specific test objectives discussed above, the rate command grappler was discovered to possess a surprising amount of versatility as a fixed base manipulator. While not directly connected with the basic test program, the grappler was tested for dexterity and found to be capable of performing a number of operations requiring coordinated maneuvers. These included picking up paper cups full of water and pouring water from one cup to another. These activities required the smooth coordination of pitching, rolling and yawing motions, together with gross slewing motions of the entire arm. Other maneuvers included "threading the needle" by insertion of a probe in a socket. While it will be granted that, for pure manipulative tasks, rate command grapplers are not as versatile as bilateral master-slave manipulators, they are believed to be well suited to the performance of mission tasks more complex than those required by this program.

7.0 DELIVERED END ITEMS

The end items of this research program deliverable at the completion of this contract are as follows:

7.1 MANIPULATOR/CONTROLLER MODULE

This assembly consists of an experimental rate command docking/anchoring manipulator, its associated position and attitude controllers, and a structural supporting pedestal which serves as the operator's control station. This pedestal also houses the necessary switching relays, voltage regulators, electronic components, electrical power supplies, terminal boards and associated interconnecting wiring.

7.2 ELECTRICAL POWER SUPPLIES

Three power supplies are furnished to permit operation of the experimental docking manipulator from a single 115 volts 60 cps AC power source. These include a 28 volt DC power supply, a 50 volt DC power supply and a 115 volt 400 cps AC power supply. An auxiliary transformer provides the 6.3 volt AC power for excitation of the control potentiometers.

The foregoing hardware items were inspected and accepted at the Contractor's facility in Dallas, Texas on 31 May 1967 by the Contracting Officer's Representative. Reference (3) contains certification of this event.

7.3 REPORTS AND DOCUMENTATION

In addition to the foregoing deliverable hardware items, this final report itself, as well as viewgraphs of all charts and motion picture films used in the final presentation are considered to be deliverable end items.

8.0 CONCLUSIONS

The following conclusions are drawn as a result of the IMM Prototype Grappler Test Program:

(1) The versatility of the overall mechanism in accomplishing the representative docking, grappling and anchoring functions was verified.

(2) The concept of controlling a docking grappler in 6 degrees of freedom with rate and acceleration commands was determined to be sound.

(3) The feasibility of functional integration of grappler and vehicle controls into a single set of selectively shared controls was verified.

(4) The concept of assigning to the grappler the same sense orientation of controls as for the vehicle was verified.

(5) The basic grappler configuration and motions were adequate to perform the simulated test missions, but it is felt that improved operation would result from:

(a) Increasing up pitch angle to 90 deg.

(b) Increasing arm extension travel to 24 in (60.9 cm).

(6) The capture of a moving target with this type of a manipulator is extremely difficult. Although this is due in part to the limitations of the test simulation, it is believed that improved performance can be obtained in the following manner:

(a) Increase the maximum rates of motion about all axes of the manipulator by approximately 50 per cent.

(b) Provide rate modulation proportional to control deflection throughout the entire range for all axes.

(7) Simulated docking could be accomplished in 3 degrees of freedom with open loop yaw attitude stabilization. However, this operation would have been greatly simplified with automatic attitude stabilization.

(8) Based upon the foregoing recommended improvements, it is tentatively concluded that with automatic attitude stabilization about all axes orbital docking could be accomplished, providing relative rates of motion between the two vehicles could be nulled to some nominal values (e.g. 0.5 fps (15.24 cm/sec) and 3 deg per sec).

9. The small statistical samples make it difficult to draw quantitative conclusions from the tests. Based on the analysis of the test runs contained in Appendix I, it can be concluded that control of the manipulator improved with practice. Average docking times following rendezvous were nearly halved between initial runs and final runs. Average times to accomplish rendezvous, however, remained fairly constant throughout. The smaller docking target, as expected, required more precise manipulator control but average docking times were only about 15 sec greater than for the tubular target.

10. The 25 lb (111.2 N) tong closure force appears to be adequate for docking, within the experience of the simulated test missions. No difficulty was encountered in docking due to lack of force sensing in the gripping tongs. The tests also demonstrated the adequacy of the present tongs for attaching to a variety of objects, and verified the wisdom of not requiring electrical power to hold the jaws at any given opening.

11. The testing demonstrated the feasibility of the basic Maneuvering Work Platform docking concept, wherein the MWP is docked head-on with one grappler, then rotated 90 deg about this attachment to permit side docking with other grapplers. No difficulty was encountered in rotating the test vehicle using the azimuth drive of the manipulator.

12. Versatility of the docking grappler far in excess of the originally intended design was demonstrated. It is concluded that a rate command grappler such as this is capable of many manipulative functions, not only in orbit but here on earth. As discussed in Appendix 11, it has been demonstrated that, when supplemented by a television data link, it is feasible to perform remote exploration missions including reconnaissance and recovery of rock specimens via remote control.

13. Some design modifications which would improve its manipulative capability are:

(a) Provide either some modulation of the gripping force or some sensory feedback of the gripping force. This could be in the form of a pre-set automatic cut-out.

(b) Modify the gripping tongs to provide a variable geometry. This might best be achieved with a three finger configuration, wherein the spacing between fingers could be altered in addition to control of jaw opening.

9.0 RECOMMENDATIONS FOR FUTURE WORK

The current contract has demonstrated the versatility and feasibility of a rate command anchoring manipulator with a 6 degree of control system selectively shared with the vehicle. Reference (1) has indicated the need for such a device in future space systems. In view of the long lead time required for development of space-operational hardware, it is recommended that a continuing effort be maintained in this technological area. Furthermore, with the knowledge gained in recent months, and in view of new developments in related fields, it is recommended that efforts in this technology area be intensified, and that additional master planning be initiated to investigate new applications and to coordinate industry activities in this field.

Specifically it is recommended that studies be initiated in order to:

(a) Investigate additional manipulator grip improvements. This program would include design, fabrication and testing of grappling and manipulating tongs of different configurations to obtain maximum versatility. Some of these would have force feedback, some only a visual readout. Designs should include articulated digits as well as three-finger configurations of variable geometry. The use of interchangeable, special purpose configurations should also be investigated. If possible these would be designed to be mounted on the existing rate command manipulator for testing.

(b) It is recommended that an additional rate command manipulator, similar to the present prototype, but incorporating all the recommended design improvements, be fabricated and tested. This could be used in conjunction with the current grappler and operated as a pair, to investigate selective controlling of more than one manipulator with a single set of controls. This would also provide an opportunity to evaluate such design improvements as increased rates, full rate modulation, etc.

(c) A design "cleanup" study should be initiated to investigate what is required to convert the "breadboard" prototype to a space-operational device.

(d) Investigate further the feasibility of controlling the rate command grappler through a remote television control link. This study should also attempt to demonstrate the sharing of television control with a remotely controlled vehicle such as the MSD-T Remote Maneuvering Unit (RMU). This study should consist of two phases, namely:

(1) Orbital docking and anchoring via a shared control TV link, with the manipulator mounted on the RMU, and

(2) The use of a vehicle which is remotely controlled via TV link for lunar reconnaissance. This vehicle which would be landed on the lunar surface, would have a remotely controlled grappler, operated via TV link, for retrieval of lunar surface specimens.

(e) Investigate the use of Voice Control for operation of a docking/ anchoring grappler. MSD-T is active in the field of voice control, having designed and fabricated a prototype voice controller with a vocabulary of 12 words specifically selected for their command application.

(f) **A** development plan should be prepared for implementation of this design, projecting development times, costs, etc., and relating them to potential applications on future programs.

(g) **A** study should be initiated to investigate the feasibility of conducting a computer simulation program, perhaps utilizing a moving base similar to the MSD-T Manned Aerospace Flight Simulator, to evaluate orbital docking and anchoring in multiple degrees of freedom.

10.0 REFERENCES

(1) "Final Report - Definition of Experiment Program In Space Operations, Techniques and Subsystems", Report No. 00.859, Volume II, dated 15 November 1966, Prepared by Advanced Space Maneuvering Systems, Missiles and Space Division - Texas, LTV Aerospace Corporation

(2) Statement of Work for Contract NAS8-21024, "Definition of Experiment Program In Space Operations, Techniques and Subsystems - Task Addendum #1", dated August 18, 1966

(3) Missiles and Space Division - Texas - Letter Number 3-30000/7L-208 dated 12 June 1967

APPENDIX I

TABULATION OF TEST RESULTS

APPENDIX I

DISCUSSION OF TEST RESULT TABULATION

The following tables summarize the results of the tests conducted under Contract NAS8-21024. These results are discussed in further detail in Section 6. 2. The tests were considered to be highly successful and all test objectives were achieved. Testing was completed in less time than originally anticipated and consumed less propellant than anticipated, as noted in 6. 2.

Three test subjects were given three trials at each of five different tests. These tests are described in Section 6. 14. Where a trial had to be aborted for some reason, the subject was allowed another trial. Due to the small statistical sample, however, it is difficult to draw quantitative conclusions in regard to time to rendezvous, time to dock and total run time.

In general, for all five tests, each subject took the longest time for the first run and generally improved his time on the second run, as one might expect. However, oddly enough, in most cases each subject took longer to complete his third attempt than his second, and in some cases, longer than his first.

On Test No. 1, in most cases, actual docking was accomplished within 30-45 sec after rendezvous (once as quickly at 13 sec). Average time to dock was 58 sec. Average time to rendezvous was 55 sec. Total run time averaged 113 seconds with one as short as 56 sec.

On Test No. 2, Subjects A and B averaged 80 sec to rendezvous and only 27 sec to dock, but Subject B experienced considerable difficulty with lateral maneuvering of the vehicle and all his trials were aborted. In most of the valid runs, docking was accomplished in 30 sec or less after rendezvous (once as quickly at 10 sec).

The average rendezvous times in Test No. 3 are approximately the same as for Test No. 1, as might be expected, since both require head-on docking with the Sixth Degree of Freedom Frame. Docking times for Test 3 averaged 71 sec. Inasmuch as the ball is a smaller target than the tube used in Tests 1 and 2, requiring more precise manipulator control, this is not unreasonable.

Head-on docking with the ball on the small Mass-Handling Platform in Test 4 proved to be a simpler task than head-on docking with the ball on the Sixth Degree of Freedom Frame in Test 3. Perhaps it is attributable to the "Learning Curve", but docking times after rendezvous in Test **4** averaged only 41 sec, with one being accomplished in eleven sec. Docking times were approximately the same as for the other head-on docking tests.

In Test No. 5, considerable difficulty with lateral maneuvering of the vehicle was experienced by all subjects. Subject **A** completed all his tests in between 85 to 145 sec, and Subject B conpleted one run in 96 sec. Due to the low lateral thrust level which hindered lateral maneuverability, further side docking tests were deleted.

TEST NO. 1
[illegible]-On Docking with Tube [illegible] 6th
Degree Frame

TRIAL NUMBER	TEST SUBJECT A	TEST SUBJECT B	TEST SUBJECT C
TRIAL 1	Run Time: 2:30 Rendezvous: 1:00 Changeovers: 8-10 Proficiency: Missed first try, O. K. on 2nd try. Technique: Yaw 90° and translated in, deploying manipulator near target. Comment: Need Yaw auto. stab. otherwise simple	Run Time: 1:32 Rendezvous: 1 min. Changeovers: ≈7 Proficiency: Missed on first try, O. K. on second. Technique: Yawed 90° and deployed arm then translated in on target - after missing repositioned arm and vehicle to make on second try. Comment: Medium use of TCA's	Run Time: 1:33 Rendezvous: 45 sec. Changeovers: ≈7 Proficiency: Technique: Scooter y[illegible] left - corrected Comment:
TRIAL 2	Run Time: 1:05 Rendezvous: 30 sec. Changeovers: 6-8 Proficiency: Good run docked on first try. Technique: After initial 90° yaw accomplished gross manipulator deployment during vehicle translation, requiring only fine positioning after reaching target. Had to correct yaw drift. Comment: Very simple, used modulation in close but was hard against stops during gross movements.	Run Time: 1:49 Rendezvous: 1:10 Changeovers: ≈ 20 Proficiency: Missed first try. Technique: Yaw 90° - position arm - translate in on target - after miss repositioned arm and maneuvered in. Comment: Hard use of TCA's	Run Time: 56 sec. Rendezvous: 43 sec. Changeovers: ≈5 Proficiency: Good Run Technique: Performed 90° yaw maneuver - deploying manipulator, made straight run into target and docked. Comment:
TRIAL 3	Run Time: ≈ 2:00 min. before abort* Rendezvous: not recorded Changeovers: 12-15 Proficiency: Waited too long to deploy manipulator, then tried to move arm after completing turn - without yaw stab., arm reaction slewed vehicle off course. *Aborted due to stuck pad on dirt particles on floor.	Run Time: 4:13 Rendezvous: 1:15 Changeovers: not recorded Proficiency: Missed first attempts, disturbing target causing it to move vertically. Missed again on second attempt as target was moving vertically. Made it on 3rd try. Technique: Yaw 90° position arm and translate in - after first miss, tried to track target up and down. After second miss, backed off then headed in and made it. Comment: Hard use of TCA's	Run Time: 1:45 Rendezvous: Changeovers: ≈3 Proficiency: Technique: Yawed 90° to left - overshot and corrected. Comment: Hard use of TCA's
TRIAL 4	Run Time: 1:32 Rendezvous: 1:04 Changeovers: Proficiency: Good Technique: Deployed manipulator early without regard to vehicle orientation then yawed to target and headed in slowly pulsing correcting heading and making fine manipulator adjustments.		

TRIAL NUMBER	TEST SUBJECT A	TEST SUBJECT B	TEST SUBJECT C
TRIAL 1	Run Time: 2 1/2 Min. Rendezvous: 1 1/2 Min. Changeovers: Proficiency: Fairly good; slight overshoot but no particular problems - except possible Vortex problem. Technique: Start head-on; translate in 10 ft; yaw right 90° extending manipulator while coasting. Overshot and had to translate left. No problem. Comments: Appears to be some Vortex problem from ventilation fans.	Run Time: Aborted after 4:04 Rendezvous: 1:00 Comment: Lateral Thrust level too low for id docking.	Run Time: 2:00 Rendezvous: 1:45 Changeovers: Proficiency: Technique: Approached target, making contact, but changing position of arm rotated vehicle off course. COMMENT: Should have positioned arm before approaching target.
TRIAL 2	Run Time: 1 Min. 10 Sec. Rendezvous: 1 Min. Changeovers: Proficiency: Good run Technique: Translated straight in then yawed 90° left ≈ five ft. from target - maneuvered manipulator into place, rotating right azimuth to reach. Comments: Turned off one ventilator fan and reduced Vortex effect.	VOID	Run Time: 1:45 Rendezvous: 1:30 Changeovers: ≈15 Proficiency: Good Run Technique: Started Head-on yawed 90° to left and translated laterally to make hookup.
TRIAL 3	Run Time: 1 1/2 Min. before Abort Rendezvous: 1 1/2 Min. Comment: Yawed too far left and translated in laterally, overshooting. Had to yaw right 180° but overshot. Aborted due to fouled overhead cable.	VOID	Run Time: 2:00 Rendezvous: 1:30 Changeovers ≈10 Proficiency: Good position but scooter thrust to right or left is too low for proper control. Technique: Comment: Hard use of thrusters
TRIAL 4	Run Time: 1 Min. before abort Translated in head-on to center of ring yawing 90° Left, then translated laterally to target, but maneuvered around excessively, finally aborting due to fouled overhead cable.		
TRIAL 5	Run Time: 1 Min. 15 Sec. Rendezvous: 45 Sec. Technique: Translate straight in to center, then retro and yaw 90°. Overshot too far to right of target. Extended manipulator and translated aft to dock. Comment: Need auto. yaw stab. to counteract vehicle rotation in azimuth.		

TEST NO. 3
Head-On Docking with Ball o 6th D
Frame

TRIAL NUMBER	TEST SUBJECT A	TEST SUBJECT B	TEST SUBJECT C
TRIAL 1	Run Time: 1 Min. 20 Sec. Rendezvous: 1 Min. Changeovers: Proficiency: Good Run - got ball on first try (however, weakness of tongs eventually let it slip out) Technique: Translate laterally 10 ft, yawing 90° left to face target. Drifted too far to left, then translated back to right (on course) then headed in.	Run Time: 3:00 Rendezvous: 1:30 Changeovers: Proficiency: Missed first attempt; backed off and missed 2nd attempt; backed off and closed making third attempt. Technique: Yawed 90° to face target, deploying manipulator as he moved in to target. Comment: Hard on thrusters	Run Time: 1:30 Rendezvous: 1:00 Changeovers: Proficiency: Good Run Technique: Yawed 90° to face target while deploying arm -- drove right into head-on dock. Comment: Light use of thrusters
TRIAL 2	Run Time: 1 Min. 45 Sec. before Abort to refill N_2 Rendezvous: Changeovers: 10-15 Proficiency: Missed on first try, disturbing target - missed on down swing and again on up swing. Aborted to save propellant. Technique: Translated straight in, yawing slightly as arm is deployed. Drifted too far to left to line up with target. Comment: Weak tongs is hurting us. - Also hard to keep vehicle stabilized in yaw to grasp ball. Trouble with operator reaction time too short to switch back and forth from vehicle yaw stabilization to an object as small as ball. However, would be worse with separate set of hand controls. Might be alleviated with hand and foot controls. Part of trouble is Vortex effect from overhead ventilators and part is due to slow(sluggish) tong closure. Note: Subsequent to this, tongs was reworked to increase grip strength and actuation speed.	Run Time: 3:46 Rendezvous: 40 sec. Changeovers: Proficiency: Slow on hand reactions. Bumped target on first attempt moving it vertically. Made two attempts to catch it as it moved vertically. Backed off until it stabilized, repositioning scooter, then approached and anchored. Technique: Yawed 90° - Position arm Comment: Hard on thrusters	Run Time: 2:15 Rendezvous: 1:00 Changeovers: Proficiency: Missed first attempt, bumping target - backed off and made new run. Technique: Rotated 90° to left to face target, deploying arm in good position. Comment: Hard on TCA's
TRIAL 3	Run Time: 1 Min. Rendezvous: 1 Min. Changeovers: Proficiency: Excellent Run Technique: Translated to center laterally, rotating slightly while extending arm, manually stabilized in yaw, extending arm and anchored first time.	Run Time: 2:30 Rendezvous: 45 Sec. Changeovers: Proficiency: Slow on hand reactions; requires too much yaw corrections (no stab.). Missed first attempt. Technique: Yawed 90° toward target deploying arm - moved in to target Comment: Hard on Thrusters	Run Time: 2:08 Rendezvous: 1:00 Changeovers: Proficiency: Made good approach but hit target, disturbing it. Backed off and made new approach, attaching to target easily on second attempt. Comment: Hard on TCA's
TRIAL 4	Run Time: 2 Min. Rendezvous: 1 Min. Changeovers: Proficiency: Technique: Rotated 90° initially while extending arm; Approached from below, coming too fast-bumped and disturbed target - caught it on the rebound coming back down.		

TRIAL NUMBER	TEST SUBJECT A	TEST SUBJECT B	TEST SUBJECT C
TRIAL 1	Run Time: 2:25 Rendezvous: 1:00 Changeovers: Proficiency: Fair - disturbed target on first attempt - got it next time Technique: Yawed 90° to face target deploying manipulator during turn - translated straight in to target drifting slightly - after first miss - backed off and maneuvered in again getting it next try.	Run Time: 1:42 Rendezvous: 1:20 Changeovers: Proficiency: Missed first try but generally good run. Technique: Deployed arm while yawing 90° to face target; translated straight in adjusting arm, disturbing on first try; backed off and repositioned; made it next try. Comment: Hard on thrusters	Run Time: 1:40 Rendezvous: 1:00 Changeovers: ≈20 Proficiency: Overshot first time but generally good. Technique: Yawed 90° to right, deploying manipulator. Translated straight in to target, overshooting. Retroed and backed up to make attachment. Comment: Moderate use of thrusters
TRIAL 2	Run Time: Abort* Rendezvous: 30 Sec. Changeovers: Proficiency: Technique: Comment: *Aborted to save propellant due to drifting of target caused by interplay of overhead cables and hoses	Run Time: 1:40 Rendezvous: 45 sec. Changeovers: Proficiency: Missed first try. Technique: Yawed 90°, deploying manipulator. Moved in on target, missed first try and disturbed target; backed off, repositioning manipulator, then maneuvered vehicle in and made hookup. Comment: Hard on thrusters	Run Time: 1:21 Rendezvous: 1:10 Changeovers: ≈20 Proficiency: Good Run Technique: Yawed 90° to right deploying arm - made head-on run in and docked, positioning arm during translation. Comment: Hard on thrusters
TRIAL 3	Run Time: 2 Min. Rendezvous: Changeovers: Proficiency: Good Technique: Extended manipulator and translated laterally until near target - retroed to stop lateral translation, maneuvered manipulator into approximate position while rotating vehicle and drove straight in to get ball first time.	Run Time: 2:00 Rendezvous: 1:15 Changeovers: Proficiency: Got confused on switchover control, commanding vehicle thrust when he intended manipulator control. Technique: Yawed 90° deploying manipulator - translated straight in to target - then backed off, repositioned and drive in again making hookup. Comment: Hard on thrusters	Run Time: [illegible] Rendezvous: 1:00 Changeovers: ≈15 Proficiency: Missed first attempt - mixed up on use of controls. Technique: After first try, backed off and docked on second try. Good run time despite trouble. Comments: Hard use of thrusters. Visibility of ball in head-on docking is poor -- must yaw wrist to see.
TRIAL 4	Run Time: 1:30 Rendezvous: ≈60 Sec. Changeovers: Proficiency: Good Technique: Yawed left to face target, raising manipulator at same time; translated straight in ≈15 ft. and retroed approximately 2 ft. from target -- corrected slight angular drift.		

TEST NO. 5
Side Docking with Ball on Mass
Platform

TRIAL NUMBER	TEST SUBJECT A	TEST SUBJECT B	TEST SUBJECT C
TRIAL 1	Run Time: 2 Min:2 Sec. Rendezvous: Changeovers: Proficiency: Fair, difficulty in holding yawed attitude. Comment: Made first approach on right hand side of target but could not dock due to interference with overhead hose. Rotated 180° and made it o.k. from left.	Unsuccessful attempts to maneuver vehicle laterally to rendezvous with target.	
TRIAL 2	Run Time: 1 Min. 25 Sec. Rendezvous: Changeovers: Proficiency: Fair - disturbed target on first attempt but got it second try. Technique: Rotated 90° left while deploying manipulator to right. Then translated laterally to right to approach target. Bumped base of tripod with vehicle but backed off and approached again getting it on second try.	Unsuccessful attempts to maneuver vehicle laterally to rendezvous with target.	DELETED FURTHER SIDE-DOCKING TESTS DUE TO POOR LATERAL CONTROL CHARACTERISTICS OF VEHICLE, IN ORDER TO REDUCE PROPELLANT EXPENDITURE AND SAVE THRUSTER LIFE
TRIAL 3	Run Time: 1:35 Rendezvous: Changeovers: Proficiency: Some trouble with angular drift. Disturbed target on first try but got it on second. Technique: Translated straight in facing target extending manipulator en route which produced counter-rotation of vehicle. Overshot and had to retro to stop forward translation - Backed off in line with target - altering arm azimuth - bumped target away but got it on next try	Unsuccessful attempts to maneuver vehicle laterally to rendezvous with target.	
TRIAL 4	Run Time: 2: 8 Rendezvous: 1: 5 Changeovers: Proficiency: Fair - difficulty with lateral translations. Technique: Thrusted head-on toward target, coasting slowly while deploying manipulator to full right azimuth, allowing counter rotation to yaw vehicle. Translated laterally to target - too far forward and had to translate aft 18". Maneuvered in close to target, having difficulty lining up, but then closed in translating laterally getting ball on first try.	Run Time: 1:36 Rendezvous: 45 Sec. Changeovers: Proficiency: Poor, overshot on initial attempt; docked on final try.	

APPENDIX II

DESCRIPTION OF RELATED TESTING TO EVALUATE FEASIBILITY OF REMOTE CONTROL BY TELEVISION

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DESCRIPTION OF RELATED TESTING TO EVALUATE FEASIBILITY OF REMOTE CONTROL BY TELEVISION

After conclusion of the testing required under Contract NAS8-21024, MSD-T undertook to evaluate the feasibility of performing useful manipulative tasks with the operator viewing the operations in a television monitor. The objective of these tests was to explore the capability of the IMM prototype grappler in the performance of various manipulative tasks associated with a remotely controlled exploration vehicle. For the concept under evaluation, the remote control requirements dictate the need for the work area to be viewed via television, thus permitting a remotely situated operator to control an unmanned exploration vehicle (on the lunar surface, for example, or possibly on the ocean bottom). The limited tests to date have indicated that simple remote manipulative tasks.can be accomplished using a rate-command TV-guided manipulator without force feedback.

For purposes of this evaluation a simulated lunar exploration mission was established which involved search recovery of rock specimens and insertion into a cylindrical cassette and screwing on of the container cap. All of these tasks were successfully accomplished using the manipulator while viewing the operations in a TV monitor. Three different camera installations were evaluated, and two different operators were used. In all cases the TV monitor was mounted on the control console ahead of the operator in such a manner as to block his direct vision of the test situation. The camera used was an Olson TV camera. Both wide-angle and standard lenses were evaluated.

For one evaluation, the TV camera was installed on the manipulator wrist assembly. A mirror was strapped to the camera so as to produce a split image in the TV monitor, with half of the image showing a side view of the tongs and the other half of the image providing a view parallel to the wrist roll axis. This arrangement provides a reference image related to the orientation of the wrist assembly, while also providing a view of the tongs. This was done in an effort to overcome the poor depth perception inherent in a conventional TV image.

Figure II-1 shows an overall view of the installation of the TV camera and the monitor mounted on the manipulator/controller module. In this photograph, the manipulator "wrist" and tongs are partially hidden by the TV camera and trapazoidal image-splitting mirror. The tubular camera support is partially visible above the camera. The TV monitor is mounted on the control console ahead of the manipulator controls.

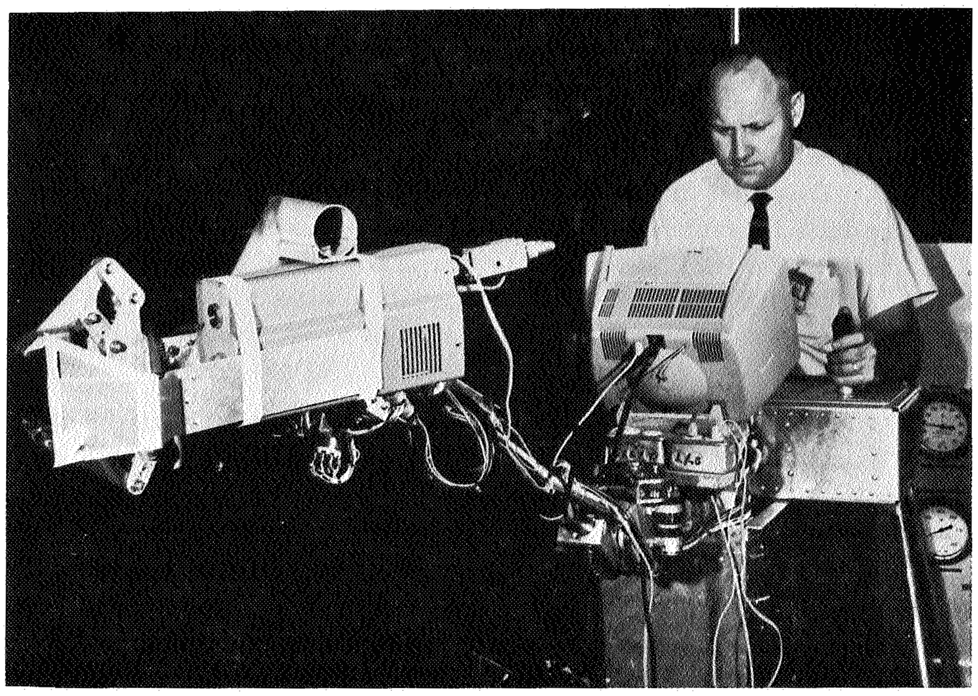

Figure II-1 - Overall View of TV Camera and Monitor Mounted on Manipulator and Control Module. Note Mirror Support Taped to Side of Camera

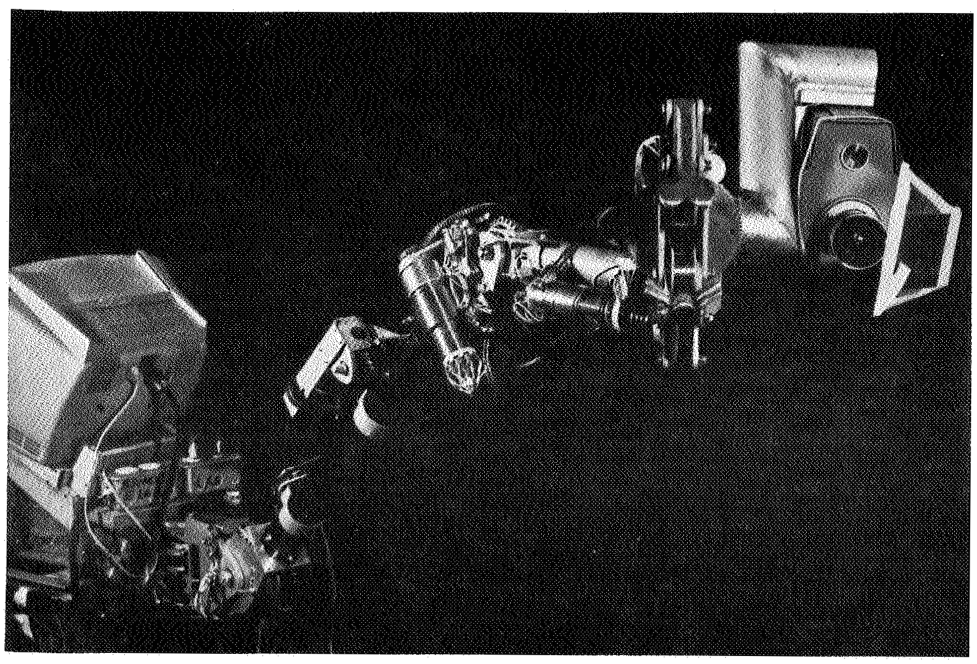

Figure II-2 - Front View of TV Camera and Mirror showing Camera Offset From Roll Axis of Tongs

In Figure II-2, which is a view looking along the roll axis of the "wrist", the Z-shaped camera support is evident. In this view it can be seen that the camera is mounted parallel to the roll axis of the tongs. The need to maintain full roll capability in the wrist necessitated offsetting the camera approximately 6 inches from the axis of the tongs to allow the tongs to clear the lens. Despite the use of a wide angle lens, the parallax caused by this offset produced a serious problem, as discussed later. Partially obscuring the camera in this view is the trapazoidal mirror which was installed at 45 deg to the camera axis to obtain a side view of the tongs. The relationship of the tongs, camera and mirror is also shown in Figure II-3.

In Figure 11-4 the operator's split-image presentation of the TV monitor is shown. On the left half of the screen the partially open tongs can be seen. This view corresponds to the mirror image which the camera would see in Figure 11-4. The other half of the image on the screen shows the straight-ahead camera view. In this photograph the manipulator can be seen approaching a large pipe coupling which was employed for this task. This coupling was used to simulate a screw-top cassette or similar container which might be used for recovery of rock specimens. The large coupling was selected because of the coarse threads. A tubular bail was welded to the top to form a handle for the tongs to grip. This coupling can be seen in more detail in Figure 11-5.

The mirror-half of the split-image in Figure 11-4 shows the tongs about to grip the tubular handle. Note that the mirror-image is rotated 90 degrees on the screen, and the tubular handle is oriented vertically, while the roll axis of the tongs is horizontal and "up" is really to the left on this half of the screen. This was a source of some confusion, but could be mastered after some practice.

The image on the right half of the screen is looking straight down on top of the coupling. The tubular handle can be seen running diagonally across the top of the large cylindrical coupling. The dark circular segment is the dark interior of the cylinder. As the tongs approach the coupling the image gets larger on the right half of the screen, but eventually moves off the screen to the right due to the parallax. Simultaneously, in the mirror-image on the left, the tubular handle moves into the center of the tongs.

Figure 11-6 is an overall view of a second test configuration. In this test, the camera was removed from the manipulator arm and mounted in a fixed position at the side so as to present the operator with a side overview of the test situation. The image on the TV screen shows the upper half of the coupling being held in the tongs just above the lower half. In this view "up" is up on the screen, but due to the camera location forward on the manipulator is to the left on the TV, and change in size of the image reflects a left-right motion of the manipulator. This presentation caused some initial confusion but could be "learned" fairly easily by the use of "shadow-ranging" and by comparing the image size with that of a known object.

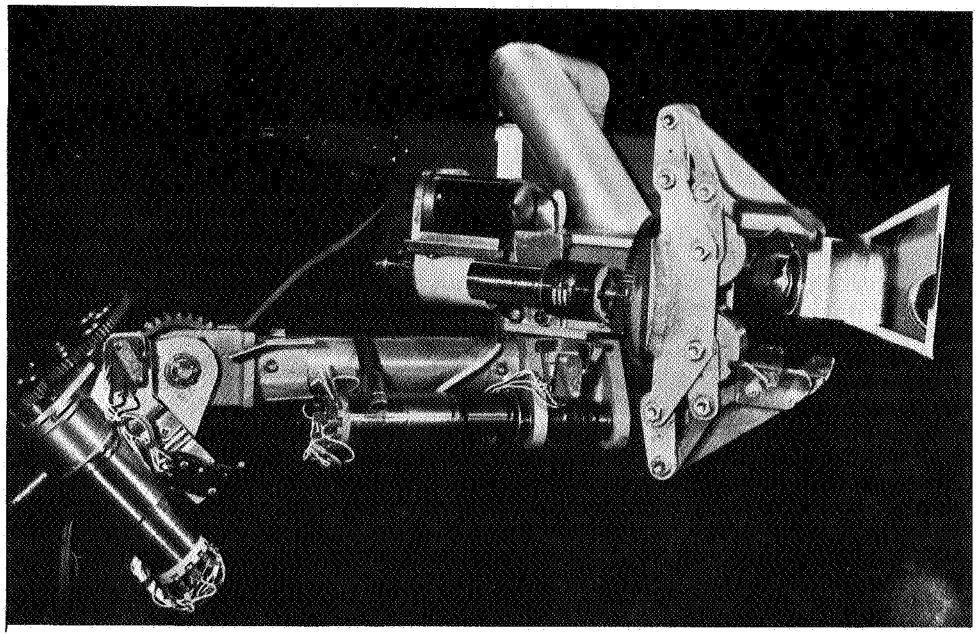

Figure II-3 - Side View of Camera and Mirror Installation Showing Relationship to Tongs

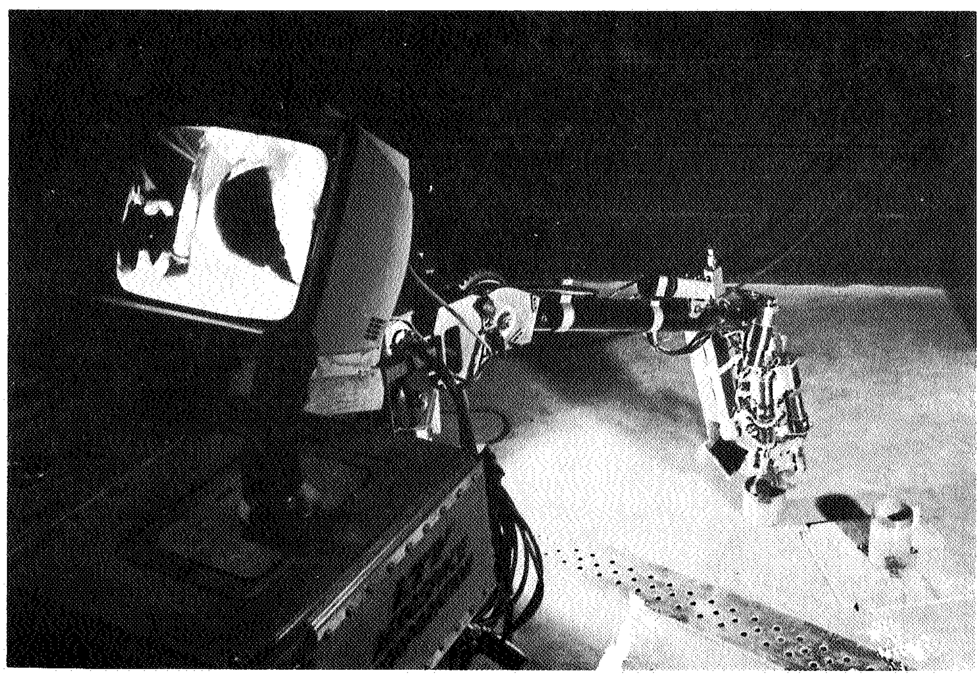

Figure II-4 - Overall View of TV Installation Showing Split-Image on TV Screen. Left Half of Image Shows Side View of Tongs Thru Mirror; Right Half of Image Looks Along Roll Axis of Tongs

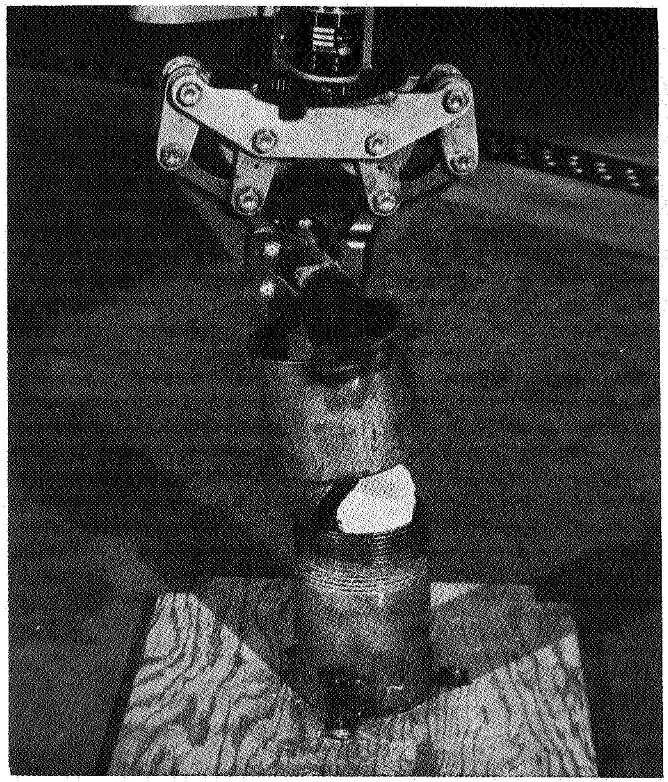

Figure 11–5 - Close up of Simulated Screw Top Cassette, Showing Tubular Handle Gripped in Tongs. Rock "Specimens" Have Been Placed in Lower Half

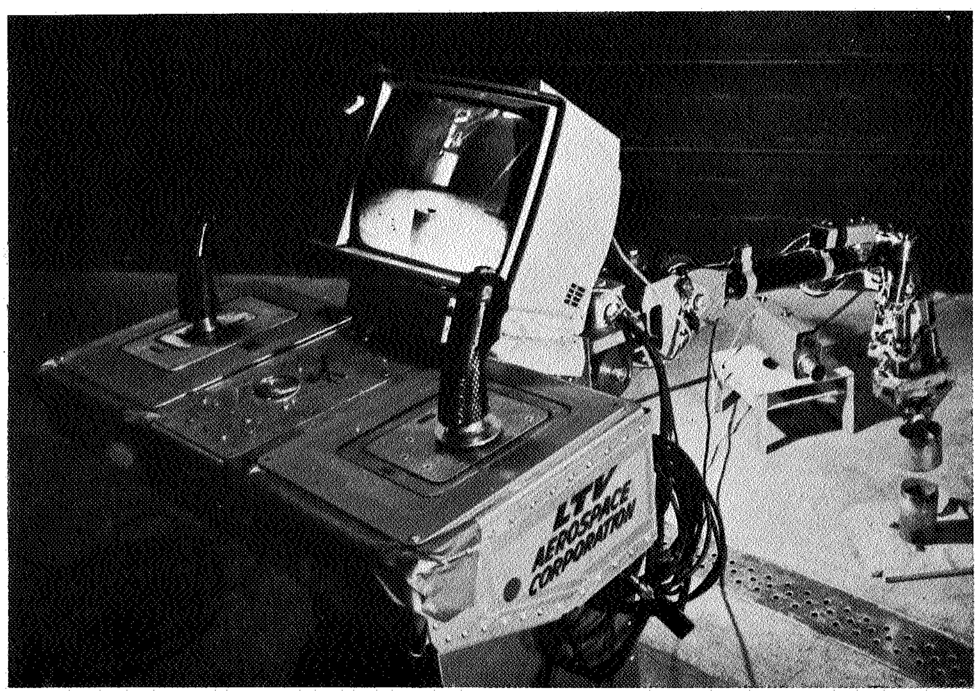

Figure II-6 - View from Operator's Station Showing Arrangement of Side-Looking TV Camera, and Overview image on TV Screen

In a third test configuration, the camera was mounted on the manipulator arm above the pitch pivot (elbow) looking along the manipulator toward the tongs. The image splitter mirror was removed and the wide angle lens was replaced with a standard lens in order to obtain greater depth of focus. With this installation a movable overview was obtained which could be controlled for search. The split-image presentation was needed because the presence of the forward portion of the manipulator on the screen aided the operator by providing a reference to assist in distance judgment. By employing the shadow-ranging technique, this configuration was successfully used to accomplish the tasks.

The set-up for these tests was admittedly rather crude due to limited time and availability of equipment. The camera was too large and heavy, and greatly reduced the mobility of the arm. The use of a split-image in lieu of a second camera caused some difficulty, but if the use of a prism or other means can be found for rotating the mirror image 90 degrees to coordinate the motions on the screen with the actual motions, this presentation would be greatly improved. However, the location of the mirror makes it very vulnerable to damage.

The problem of parallax is also quite serious, in that the working range in which both images could be seen simultaneously was quite small. The use of an additional camera to present an overview would have been very helpful in this regard. Furthermore, some way must be devised to get the forward view closer to the center line of the tongs. This would probably require a redesign of the wrist and tongs, and the use of a smaller camera.

Another factor which proved to be very critical was lighting intensity, in that it has a strong effect upon depth of focus. In actual practice it may be necessary to mount a light, or lights, on movable booms so that they can be controlled by the operator. The use of shadow-ranging was very helpful in overcoming the poor depth perceptions.

In conclusion, these tests have demonstrated the feasibility of conducting remote exploration by television, and have shown that a remotely controlled manipulator, with TV guidance, is capable of recovering rock specimens for return to earth. However, a number of improvements in the system are necessary to improve operator dexterity. It is recommended that this effort be continued in order to achieve an operational system capable of remote exploration.